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Stroke- and Space-Resolved Slit Spectra of Lightning*

by

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* Other volumes covering different aspects of the 1965 ARPA-AEC Joint Lightning Study at Los Alamos are:

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STROKE AND SPACE RESOLVED SLIT SPECTRA OF LIGHTNING

BY

T. Robert Connor

ABSTRACT

Twenty-four stroke-resolved slit spectra of lightning taken in 1966 are presented, one of which is also the first space-resolved slit spectrum of a return stroke.

These split spectra unambiguously show that the lightning return-stroke channel is a strong continuum source and that the continuum observed in the slitless spectra in 1965 is real and not the result of line radiation scattered from natural backgrounds such as clouds, haze, or rain.

Reduced slit and slitless lightning spectra now available indicate differences among strokes, both in continuum shape and relative line intensity. For most strokes the continuum can be fitted by a straight line, and the measured 3900- to 6900-Å continuum ratio varying between 1.3 and 2.4 can be explained by an optically thin bremsstrahlung source with electron temperatures between 18,000 and 50,000°K. Some strokes have a ratio larger than 2.4, and may be intermediate between optically thick and thin, since at a given electron temperature this ratio becomes larger as the source becomes optically thicker. Other continua cannot be fitted by a straight line, and some of these agree with published results. The spectrum near 3914 Å is essentially continuum.

A blend of NII, OI, and OII multiplets near 4630 Å is much stronger for slit spectra than for slitless, but all-sky photometric data show that this feature is variable. Furthermore, the intensity of multiplets between 4000 and 4250 Å agrees with slitless spectra for some strokes, while for others it is much stronger. These variations indicate real differences in the data sample, not instrumental effects.

The average width at half-intensity is the same for slit and slitless spectra for all strong line features except H_α. One possible explanation is that the channel's electron density, which determines Stark broadening of H_α, averaged twice as large in the 1965 study as in 1966.

Another possibility, suggested by the space-resolved spectrum, is that in some of the slitless spectra the observed Hα line width was partly due to its space profile. In agreement with slitless spectra, the Hα line is generally weaker for first than for subsequent return strokes, and the ratio of NII to NI radiation and the slope of the continuum indicate a higher temperature, on the average, for first return strokes.

For those strokes whose continuum is fitted well by a straight line, the 5000-Å blend of NII multiplets looks like a good lightning discriminant for Vela systems. For strokes whose continuum drops strongly from 4000 to 5400 Å and rises again at longer wavelengths, it seems less feasible. A quantitative treatment of the best channel for discrimination must be delayed.

The space-resolved spectrum shows that the time- and wavelength-integrated brightness of the line radiation from three strong line features at 4630, 5000, and 5680 Å, and of the total visible light, falls to half central brightness ~ 8 meters from the channel center, while 6563 Hα line radiation falls to half central brightness in ~ 34 meters and is above instrument threshold out to ~ 120 meters. Emission at such large distances must be caused by lateral corona currents. This was an unusual stroke, and dimensions of all other strokes were too small to be resolved.

I. INTRODUCTION

During data reduction of stroke-resolved slitless lightning spectra[1] obtained as part of the 1965 ARPA-AEC joint lightning study at Los Alamos, the question arose whether what appeared to be continuum in the slitless spectra might not be due largely to light scattered from clouds, rain, and aerosol near the channel. An attempt was made in the summer of 1966 to answer this question. The N4GS lens and grating spectrograph used for the slitless spectroscopy and described earlier[1] was operated with a vertical entrance slit at the focus of the objective lens and with a 90° image rotator in front of the objective lens. With this arrangement a vertical lightning channel is imaged horizontally across the vertical entrance slit. If there is no light scattered near the channel, and if the channel diameter is unresolved by the objective lens, that part of the channel imaged on the entrance slit acts as a pinhole entrance aperture and its spectrum is displayed as a horizontal line in the film. If, however, a significant amount of light is scattered or emitted on either side of the channel, then the spectrum of this light is displayed above and below the spectrum of the channel core.

Hundreds of stroke-resolved slit spectra of lightning were obtained in the summer of 1966 by this technique, but only 24 were judged suitable for reduction and reported here. Only one of the 24 had sufficient light scattered or emitted near the channel to give an exposure allowing spatial resolution of this light.

II. STROKE-RESOLVED SLIT SPECTROSCOPY OF LIGHTNING

A. Apparatus

The spectrograph used is the N4GS lens and grating spectrograph[2] with a film-aperture ratio of f/2.8 and a dispersion of 90 Å/mm. A 90° image rotator made of two glass prisms was placed in front of the objective lens to image the vertical lightning channel horizontally across the vertical entrance slit. The spectrograph's horizontal field of view was 16°. The spectra taken on September 7, 1967 were obtained using a 200-μ entrance slit (this corresponds to ~ 6.5 Å in the film plane); for all

other spectra the slit width was 100 μ. The width at half-intensity for lines of a mercury source was 5 ± 1 Å (the entrance slit width was 100 μ, and the densitometer slit width was 25 μ). To improve the signal-to-noise ratio in the lightning spectra, they were densitometered with a slit 125-μ wide, giving an instrumental width of ~ 10 Å for the reduced spectra. Eastman Kodak 2475 film was used.

The spectrograph calibration was determined at 50-Å intervals. The calibration and method of data reduction have been described earlier.[1]

B. Results and Discussion

1. Reduced spectra - The 24 spectra are presented in Figs. 1 through 24, at the end of this report. The abscissa in each case is wavelength in Angstroms, and the ordinate is time-integrated flux (erg/Å cm^2) at the entrance slit. This flux emanates from a vertical length of channel specified in the figure caption. Each spectrum is corrected for air and water vapor transmission, but it was not possible to correct for rain transmission.

2. Continuum shape - The continuum level is reasonably easy to determine between 4500 and 6400 Å, but for some spectra it is difficult to say whether there are strong bumps in the continuum between 4000 and 4300 Å and between 6400 and 6700 Å, or whether these bumps are due to a high density of overlapping lines. There is no correlation between the presence or absence of these bumps and the magnitude of the flux at the entrance pupil which would indicate an instrumental effect or error in calibration.

Between 6400 and 6700 Å the strongest identified lines are Hα and NI (20, 21, 22, 31), as can be seen, for example, in Fig. 7 (count 32, scan 3). The lines are sharp, and there is no bump. However, Figure 5 (count 32, scan 1), which has about the same continuum level (4500 to 6400 Å), shows a bump in this wavelength region. If the bump is due to the same lines, they must have become exceedingly diffuse. Orville's time-resolved spectra[3] show that the Hα feature can be extremely broadened by the Stark effect in the first few microseconds of a return stroke, and, since the quartet-quartet NI transitions are also strongly broadened by the Stark effect, it is conceivable that in the early time history of the stroke these lines could be strongly broadened and produce the observed bump.

To appreciate the problem of determining the continuum level between 4000 and 4300 Å, consider again Figs. 5 through 7 which are spectra of three return strokes of one flash. If the level of the continuum were drawn just below the obvious line features, then in Fig. 5 there would be a sharp rise in the continuum near 4300 Å and a sharp drop again near 4000 Å; in Fig. 7, the rise and drop of the continuum in this same wavelength range are not so sharp, and in Fig. 6 there is a question whether the continuum really rises quickly at 4300 Å and drops sharply at 4000 Å, or rises gradually from 4600 to ~ 4100 Å with a strong absorption feature near 4300 Å (there is a well-documented but unidentified atmospheric absorption feature at ~ 4300 Å which has been observed by Russian workers).[4,5]

Strong, sharp, 200- or 300-Å-wide bumps in the continuum are difficult to explain theoretically, as are absorption bands that are strong in one stroke of a flash and absent from the next stroke. It would be most satisfying to conclude that the bumps are due to lines, but there may also be theoretical problems for this conclusion, since the ratio of the total energy radiated by NII (12, 40, 30, 65, 42, 33, and 48) to that radiated by NII (3) is only ~ 2 at 20,000°K, or ~ 6 at 40,000°K, and the ratio of the total energy radiated by NI (10, 6, 4, and 5) to that by NI (20) is ~ 8.3 at 10,000°K, or ~ 6.6 at 40,000°K. It is therefore impossible to account for the bump quantitatively in all cases by considering only the NI and NII species.

A large fraction of the spectra can be closely fitted by a straight line if the strong bumps discussed above are attributed to line radiation. The shape of the continuum for these strokes is then in agreement with that reported in LA-3754, and can be explained by a bremsstrahlung source. For electron temperatures between 18,000 and 28,000°K, optically-thin bremsstrahlung continuum has a fairly linear wavelength dependence throughout the visible, with a 3900- to 6900-Å continuum ratio of ~ 1.3 at 18,000°K, and ~ 1.8 at 28,000°K. Even at electron temperatures as high as 50,000°K, the visible continuum, although becoming slightly concave, can be fitted by a straight line to within 10%, and the 3900- to 6900-Å continuum ratio is ~ 2.4. Larger ratios result at a

given electron temperature as the source becomes optically thicker.

There are spectra (see Figs. 8, 9, 19, 21) which are not simply explained in terms of bremsstrahlung radiation. Their continuum falls so fast from 4000 to 5500 Å that it must be assumed that the early high temperature phase of the channel was intermediate between optically thin and thick, while the rise in the continuum towards longer wavelengths could be due to emission, either of long duration or at higher than normal electron densities, late in the channel history when electron temperature had dropped below 11,000°K.

The continuum spectrum agreement for slit and slitless spectra is good. The best agreement is between the first return stroke (slitless spectrum) of run 40, count 171, 1965, and the first return stroke (slit spectrum) of count 76, September 7, 1966. For these two strokes, even the line-to-continuum ratio is about the same, although there is a slightly different intensity distribution among the lines. As for the 1965 spectra, the continuum generally falls off more quickly from blue to red for first return strokes than for subsequent return strokes, indicating a higher temperature for first return strokes in most cases.

The spectra have been compared with continuum spectra published by Orville and Uman,[6] and certain of their continua are found to agree with spectra shown here in Figs. 3, 8, 9, 17, 19, and 21 except that in a few cases their continuum at 5000 Å is too large for agreement. Many spectra presented here have continuum which is too linear throughout the visible to agree with Orville and Uman's results, and they have a few strokes whose continuum is too strongly peaked near 4000 Å to agree with my results, but this is probably due to differences in data sample.

3. Line features - The blend of NII, OI, and OII multiplets near 4630 Å is much stronger for the 1966 sample of flashes than for 1965's sample, but data* taken with 160° field of view photoelectric detectors operated by EG&G during the 1965 summer study also indicate that this feature is variable from stroke to stroke and from storm to storm. Furthermore, Salanave et al. have shown that for a given stroke, the relative intensity of this feature varies along the height of the channel.[7] The blend of multiplets between 4000 and 4250 Å agrees with slitless spectra for some strokes, while for others it is much stronger. These variations indicate real differences in the data sample and are not instrumental effects.

The question was raised in LA-3754, whether scattering or light emission close to the channel could result in apparently broader lines for slitless spectra. The half-width (width at half-intensity) has been measured for a number of line features, and the average half-width and mean deviation are listed in Table I for slit and slitless spectra. The average half-width agrees within the mean deviation for all lines except Hα. Nonresonant scattering cannot explain this difference, and one possible explanation is that Stark broadening was larger for the sample of slitless spectra than for the slit spectra. A tabulation of Stark-broadened line profiles for hydrogen[8] shows that a factor of two difference in electron density can account for the difference in line width. Another possible explanation, suggested by the results of the space-resolved spectrum, is that in some of the slitless spectra the observed Hα line width was partly due to its space profile. As in spectra from 1965, the Hα line is generally weaker for first return strokes than for subsequent return strokes, and the ratio of

* Not yet published.

Table I.

Average Half-widths of Line Features for Slitless and Slit Spectra

Wavelength of feature (Å)	3995	5000	5680	5940	6158	6478	6563	6644
Slitless Half-width (Å)*	9±2	17±3	13±2	19±4	28±5	20±3	27±3	22±3
Slit Half-width (Å)*	8±1	15±2	16±4	19±2	24±4	19±5	18±2	22±4

* Not corrected for instrumental width.

NII to NI radiation, which is a measure of the degree of excitation, is larger for first than for subsequent return strokes.

4. Space-resolved lightning spectrum - The spectrum in Fig. 22 corresponds to a densitometer trace made along the dark central part of the space-resolved spectrum. Other densitometer tracings were made at 50-μ intervals on both sides of the first, out to 200 μ. There is actually exposure out to 400 μ, but that beyond 200 μ became too poor to yield good spectra. This exposure is not due to time smear, because two photoelectric channels (at 3914 and 6563 Å) whose field of view included ~ 200 meters of the lightning channel indicate that the intensity of the channel rose and decayed two decades in about 500 to 600 μsec. The channel would have had to radiate for $\gtrsim$ 16 msec if the exposure were due to time smear. Furthermore, it is not due to overexposure, since other spectra of greater exposure do not show this effect. The exposure is therefore due to light emitted or scattered either side of the center of the vertical channel.

The apparent brightness 28 meters from the channel center is orders of magnitude greater than would be expected for light scattered either from heavy rainfall or from a cloud behind the channel. Furthermore, the strong change in shape of the continuum at points away from the channel center indicates that the scatterers or reflecting surface are dispersive. I must therefore conclude that there is strong light emission from points as far as 31 meters from the channel center, and that at 6563 Å the apparent brightness is above threshold out to ~ 120 meters.

The time- and wavelength-integrated brightness of all visible light (all line plus continuum radiation between 3900 and 6900 Å except the Hα line) emitted by the channel falls off exponentially as a function of distance from channel center out to approximately 31 meters, at which point it still decreases, but quite slowly. A similar dependence was found for atomic line emission of three strong line features at 4630, 5000, and 5680 Å, and in all four cases the brightness dropped to half the channel center brightness in ~ 8 meters. However, the time- and wavelength-integrated brightness of the Hα line has an exponential dependence out to at least 62 meters, and has dropped to half central brightness in ~ 34 meters.

The fact that the half-width of the spatial brightness profile is four times larger for Hα than for the other emission lines or for the total visible light can also explain the difference in Hα line width for the slit and slitless spectra.

The continuum for the channel core can be fitted very well by a straight line throughout the visible except for a slight bump in the vicinity of Hα. At ~ 15 meters from channel center, however, the continuum has a strong, broad bump peaking near 4750 Å and another peaking between 6500 and 6700 Å. There are minima at ~ 5700 and 4150 Å with a rising continuum at wavelengths shorter than 4150 Å. The shape of the continuum for the channel core can be explained in terms of bremsstrahlung radiation, but I presently have no physical interpretation for the shape of the continuum at points off channel center.

I can only conclude that the emission at such great distances must be excited by a lateral flow of current between the lightning channel and highly charged air surrounding it. To demonstrate the plausibility of this, Fig. 25 shows an enlarged photograph of a lightning flash from the 1965 study (count 393 of run 30). It was taken at night using a red filter (~ 500-Å half-width, peak at ~ 6350 Å) in front of a 63-mm, f/4 lens. The range was measured as 13.4 km by photographic triangulation. The main channel between cloud and ground is ~ 2.4-km long. There are many branches off the main channel into the surrounding air, indicating that the air was highly charged. The width of these branch strokes indicates the resolution limit of the camera. The main channel to ground consists of a bright core, whose diameter is also unresolved by the camera, and a broad emitting region whose diameter varies from ~ 150 meters near the cloud to ~ 200 meters near the ground. The uniformity of the brightness in this region leads me to conclude that the emission is due to a corona-type discharge.

Lateral corona currents were first discussed by Bruce and Golde[9] to explain observations of electric field changes, and have been treated mathematically by Pierce[10] and by Rao and Bhattacharya.[11] The time history of such phenomena is about one to a few millisec so that little or no time smear would

be expected in the record for count 91, and the symmetry of the exposure indicates that there was no time smear.

In the discussions of lateral corona currents just mentioned, the current is said to drain away charge deposited along the path of the stepped leader, and the diameter of stepped leaders has been reported to vary between 1 and 10 meters.[12] The emission 120 meters from the channel must therefore be caused by draining away of charge which was not deposited in the air by the stepped leader.

The fact that the Hα emission becomes so much stronger relative to the rest of the spectrum is also consistent with a corona current excitation process, for it is well known that water drops in high electric fields (fields that would exist between the channel core and the surrounding space charge) give off a corona discharge.[13-15] This discharge at the surface of the drop could produce large quantities of hydrogen even when the temperature became too low to excite NII or bremsstrahlung continuum radiation.

III. CONCLUSIONS

In LA-3754 it was concluded that the image of the lightning channel at the entrance aperture did, indeed, act as an entrance slit, and that the continuum seen by the slitless spectrograph was therefor truly continuum. The slit spectra unambiguously show that the lightning channel is a strong continuum source and that the spectrum near 3914 Å is essentially continuum. Furthermore, considering only those strokes from 1966 which gave good spectra, only one in 24 gave significant exposure at distances of one resolution limit beyond the channel center. For 23 of the 24, the channel image at the entrance aperture would, indeed, have acted as an entrance slit if this spectrograph had been operated in a slitless mode. There are, however, storms such as run 30 of the 1965 lightning study in which a large fraction of the flashes photographed show strong emission out to large distances either side of the main channel, and a great deal of branching of the main channel into the highly charged air. For such storms the assumption that the channel image acts as an entrance slit might not be valid. However pictures of the 1965 flashes for which spectra were obtained show little channel branching and no emission about the unresolved channel core, so the assumption must be considered valid.

The larger sample of reduced lightning spectra now available indicates differences in the spectrum of lightning for different strokes, both in the shape of the continuum and in the relative intensity of the lines. The width of the Hα line was, on the average, larger for the 1965 slitless spectra than for the 1966 slit spectra. This is possibly due to a factor of two difference in electron density in the volume emitting Hα, or part of the width of the line might have been due to a spatial profile in the case of the slitless spectra.

Agreement has also been found between the continuum of a few strokes and a few of the results published by Orville and Uman.[6] Many of the strokes have a continuum that can be fitted well by a straight line and can therefore be explained in terms of a bremsstrahlung source. In some cases the large 3900- to 6900-Å continuum ratio suggests that the continuum is intermediate between optically thin and thick.

The space-resolved lightning spectrum shows strong volume emission out to ~ 30 meters from the channel core, and in the vicinity of Hα this emission is above the instrumental threshold out to ~ 120 meters. This emission has been attributed to excitation by lateral corona currents.

Since a qualitative discussion was presented in LA-3754 regarding the feasibility of using a narrow channel at 5000 Å for lightning discrimination for Vela Sierra detection systems, a comment about the bearing of the slit spectra on this problem is appropriate. The slit spectra, whose continuum can be fitted by a straight line and for which the blend of lines between 4000 and 4250 Å is of weak to moderate strength, are very similar to the slitless spectra. Consequently, for these, a 20-Å-wide discrimination channel centered on the blend of NII multiplets near 5000 Å may be as good or better a discriminant, under a variety of storm and background light conditions, than one at either 4150 or 6563 Å. For the slit spectra for which the blend of lines between 4000 and 4250 Å is strong or for which the continuum drops

steeply from 4000 Å toward longer wavelengths, a 5000-Å channel will not be so much better than, and may not be so good as, a 4150- or 6563-Å channel. However, a quantitative treatment of the best channel for discrimination must be delayed for presentation in another report.[16]

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I thank Herman Hoerlin for pointing out the desirability of having stroke-resolved slit spectra of lightning, and G. E. Barasch for his helpful discussions and for his correlated data from collimated photometers. I thank C. Stevens for his help with calibration of the spectrograph, L. M. Duncan for her effort in densitometry and the running of computer programs, and D. L. Stam for illustrations. I also thank Judy Sul for her fine secretarial work.

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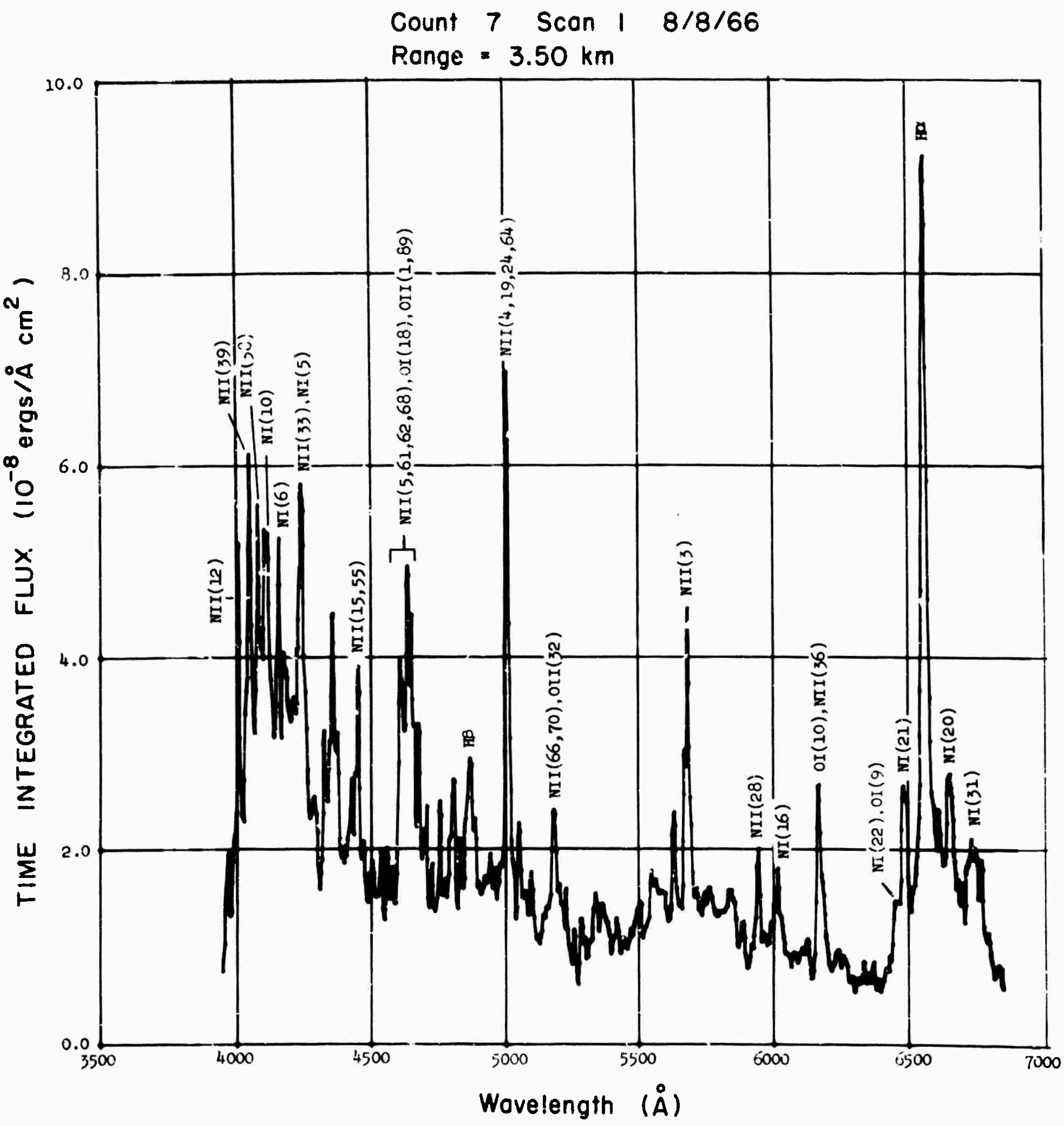

Fig. 1. Flux at spectrograph entrance pupil from ~ 6-meter length of channel, uncorrected for rain transmission. First return stroke.

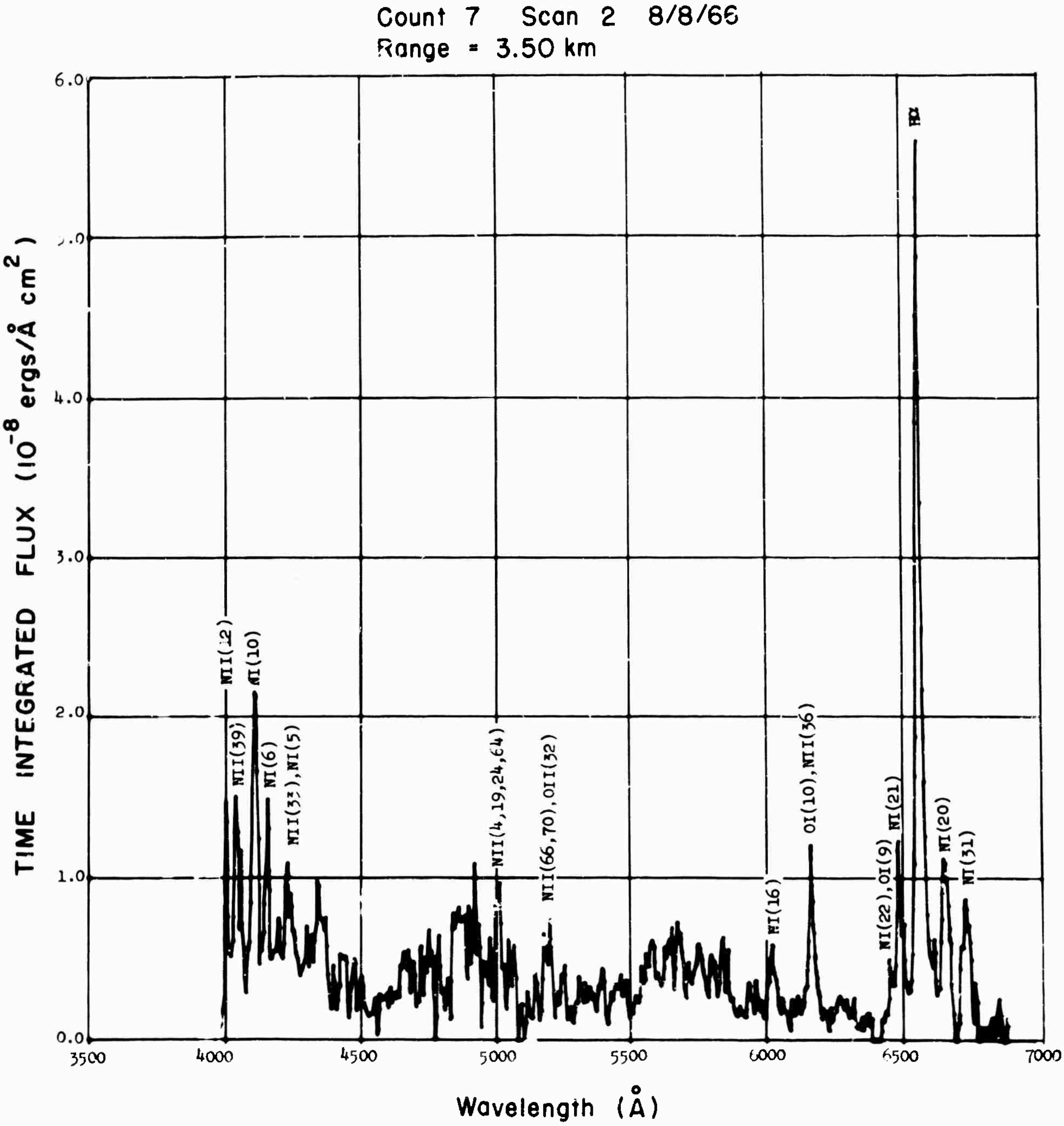

Fig. 2. Flux at spectrograph entrance pupil from ~ 6-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

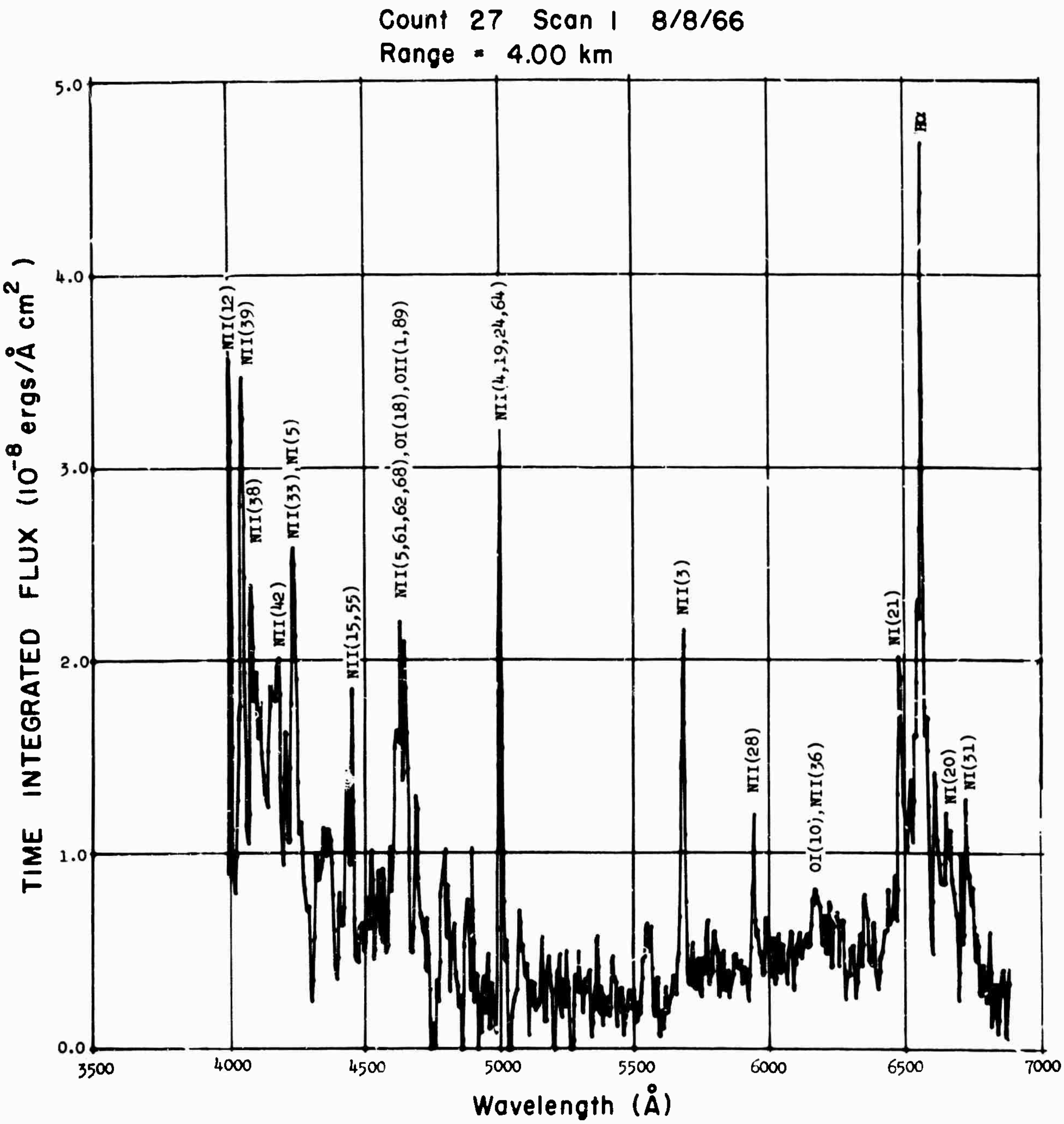

Fig. 3. Flux at spectrograph entrance pupil from ~ 6-meter length of channel, uncorrected for rain transmission. First return stroke.

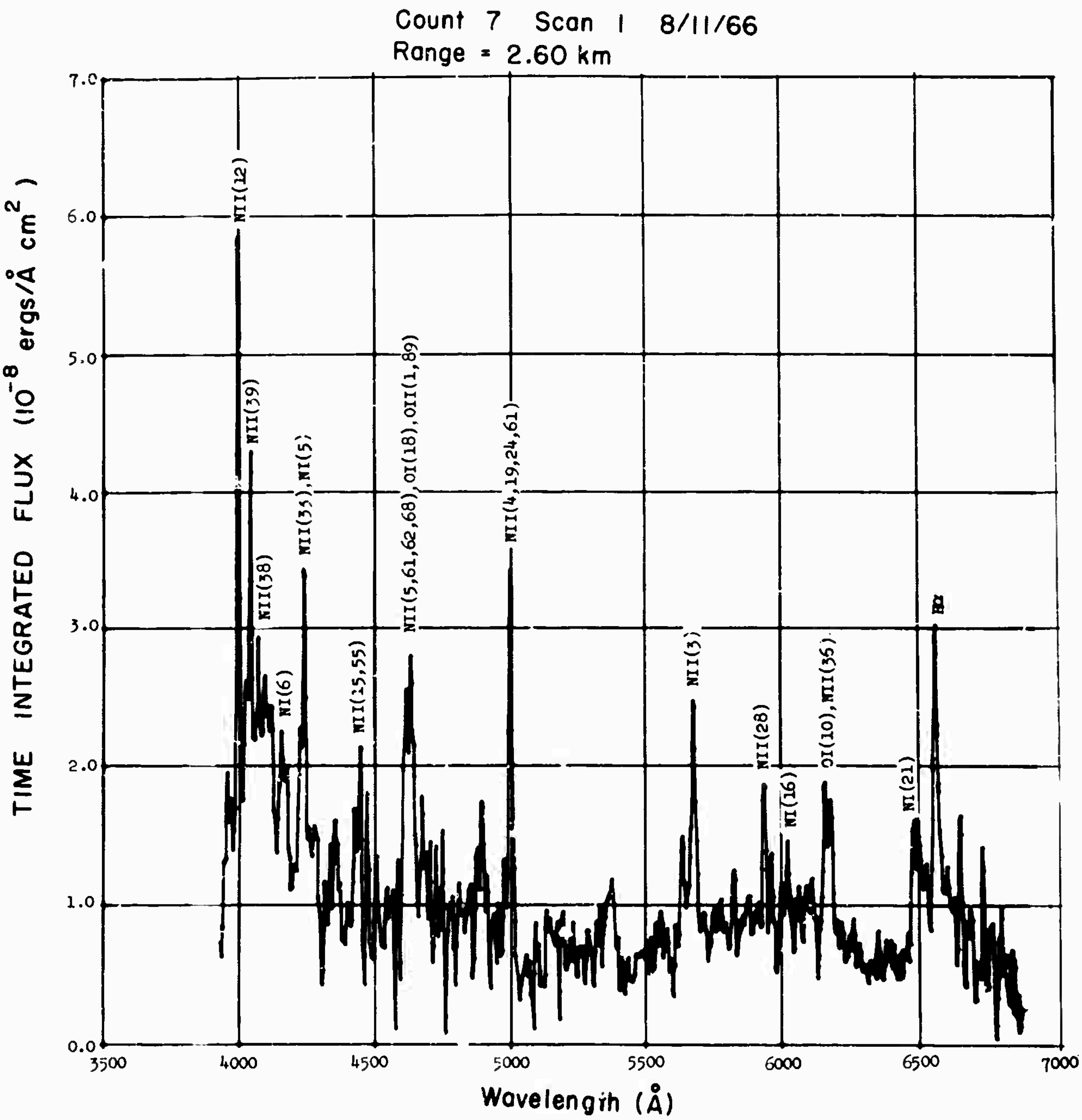

Fig. 4. Flux at spectrograph entrance pupil from ~ 1.6-meter length of channel, uncorrected for rain transmission. First return stroke.

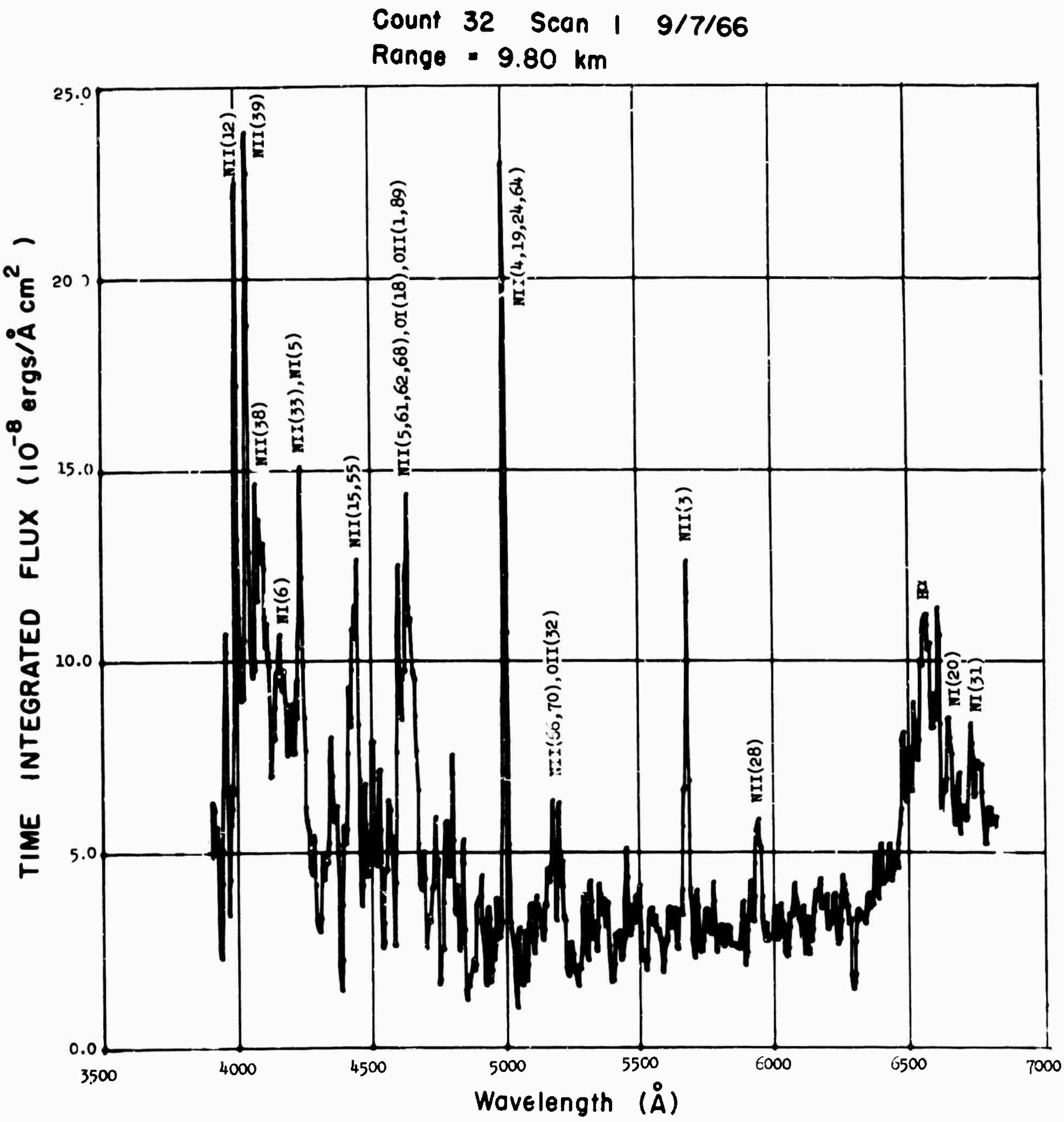

Fig. 5. Flux at spectrograph entrance pupil from ~ 31-meter length of channel, uncorrected for rain transmission. First return stroke.

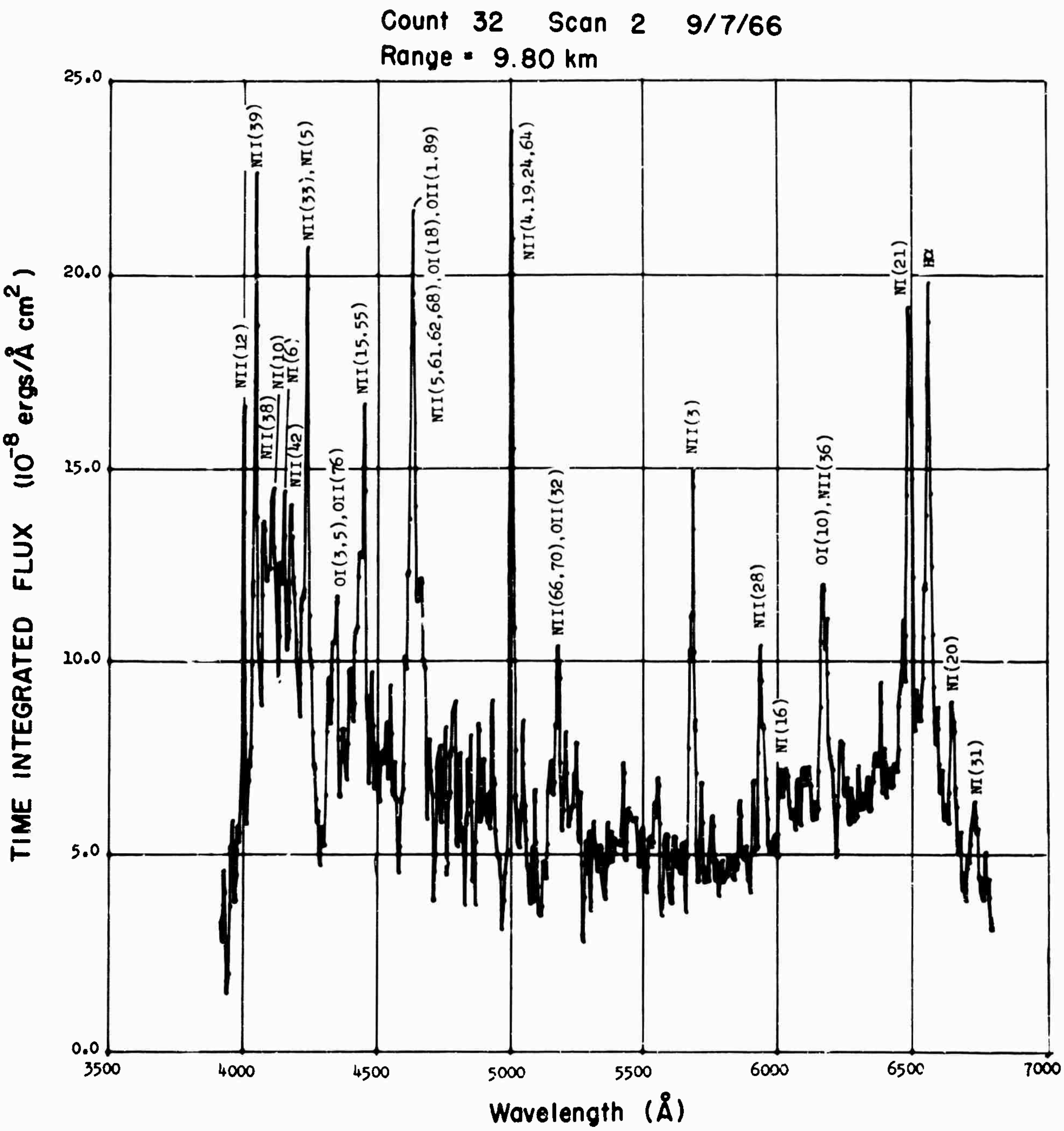

Fig. 6. Flux at spectrograph entrance pupil from ~ 31-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

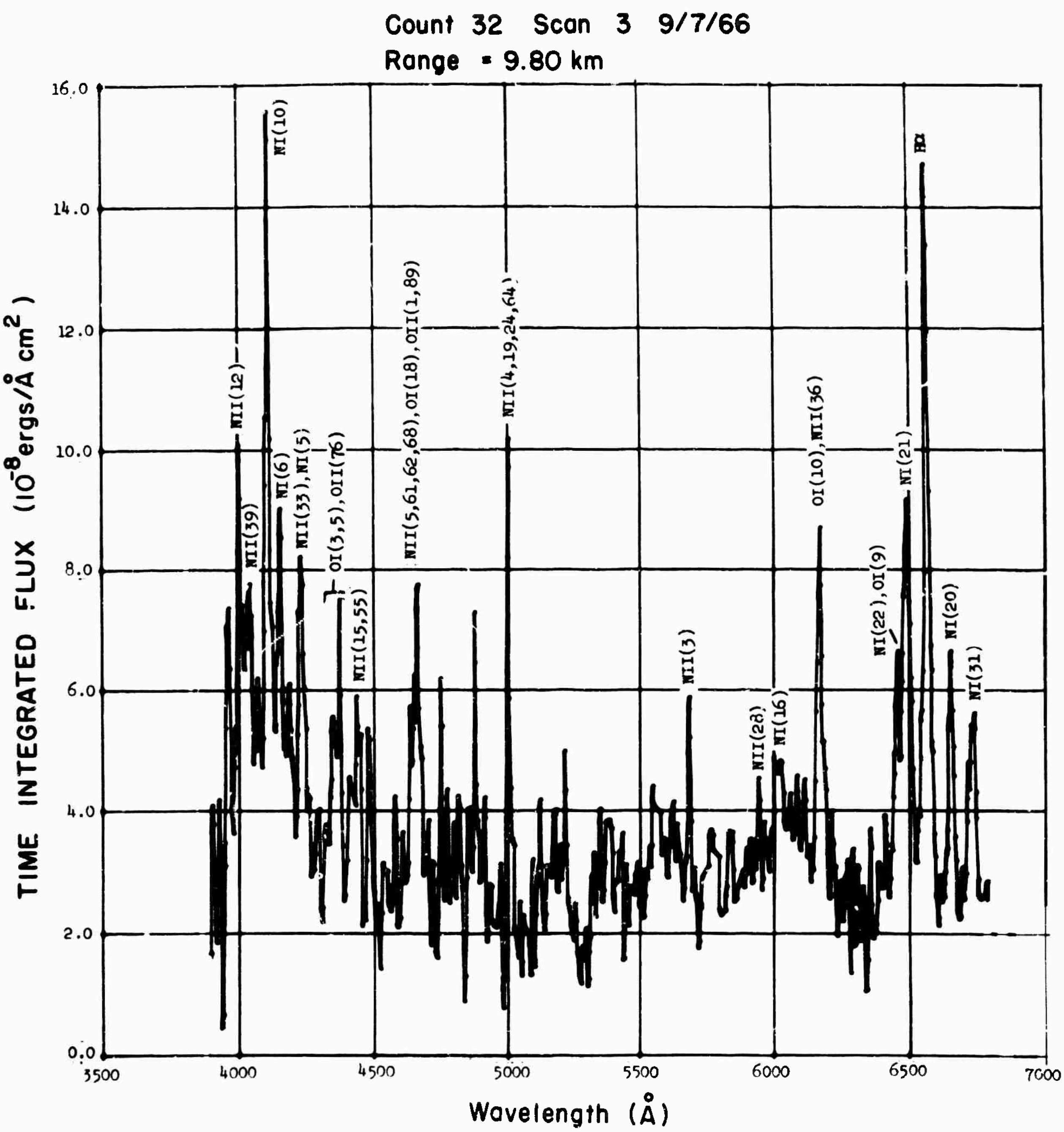

Fig. 7. Flux at spectrograph entrance pupil from ~ 31-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

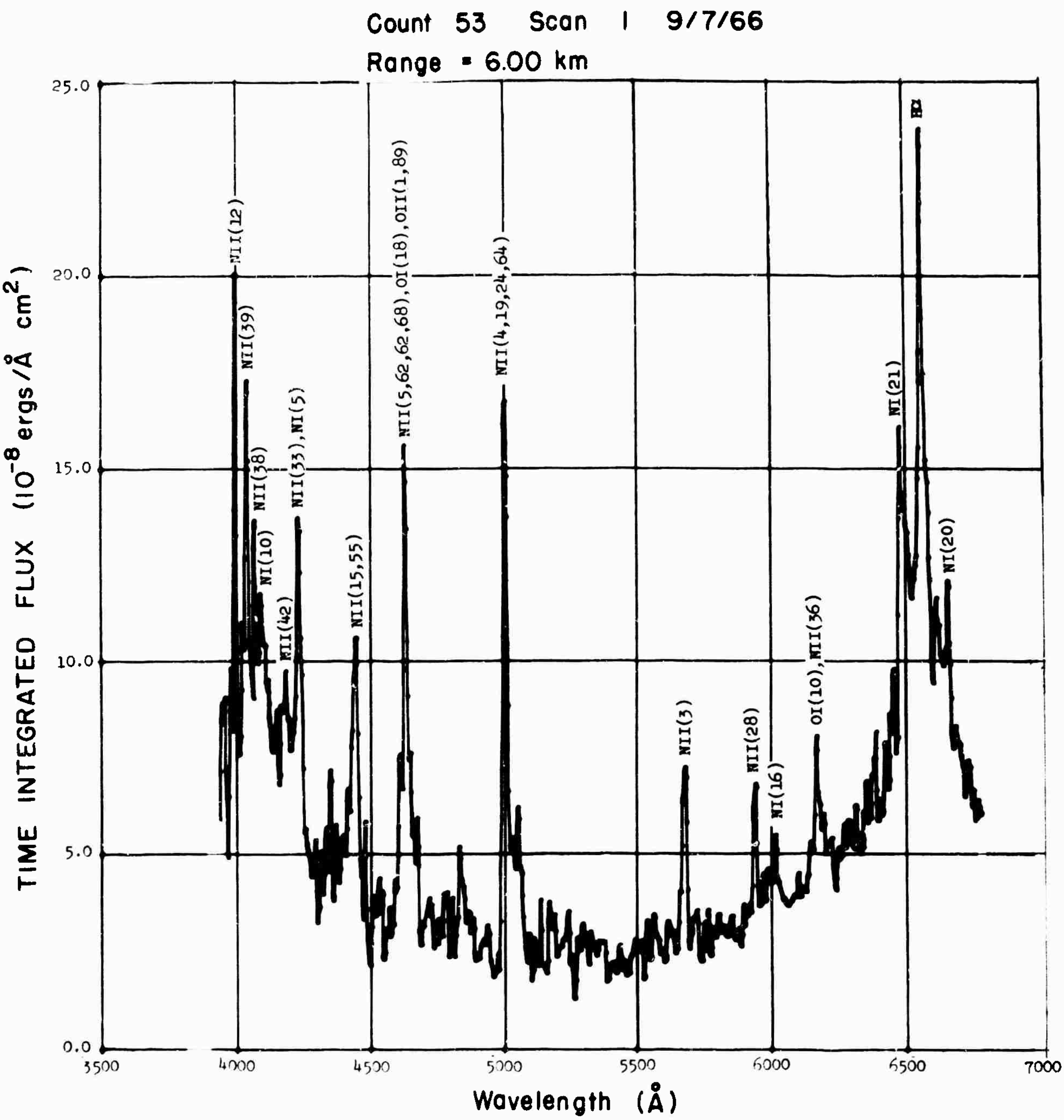

Fig. 8. Flux at spectrograph entrance pupil from ~ 19-meter length of channel, uncorrected for rain transmission. First return stroke.

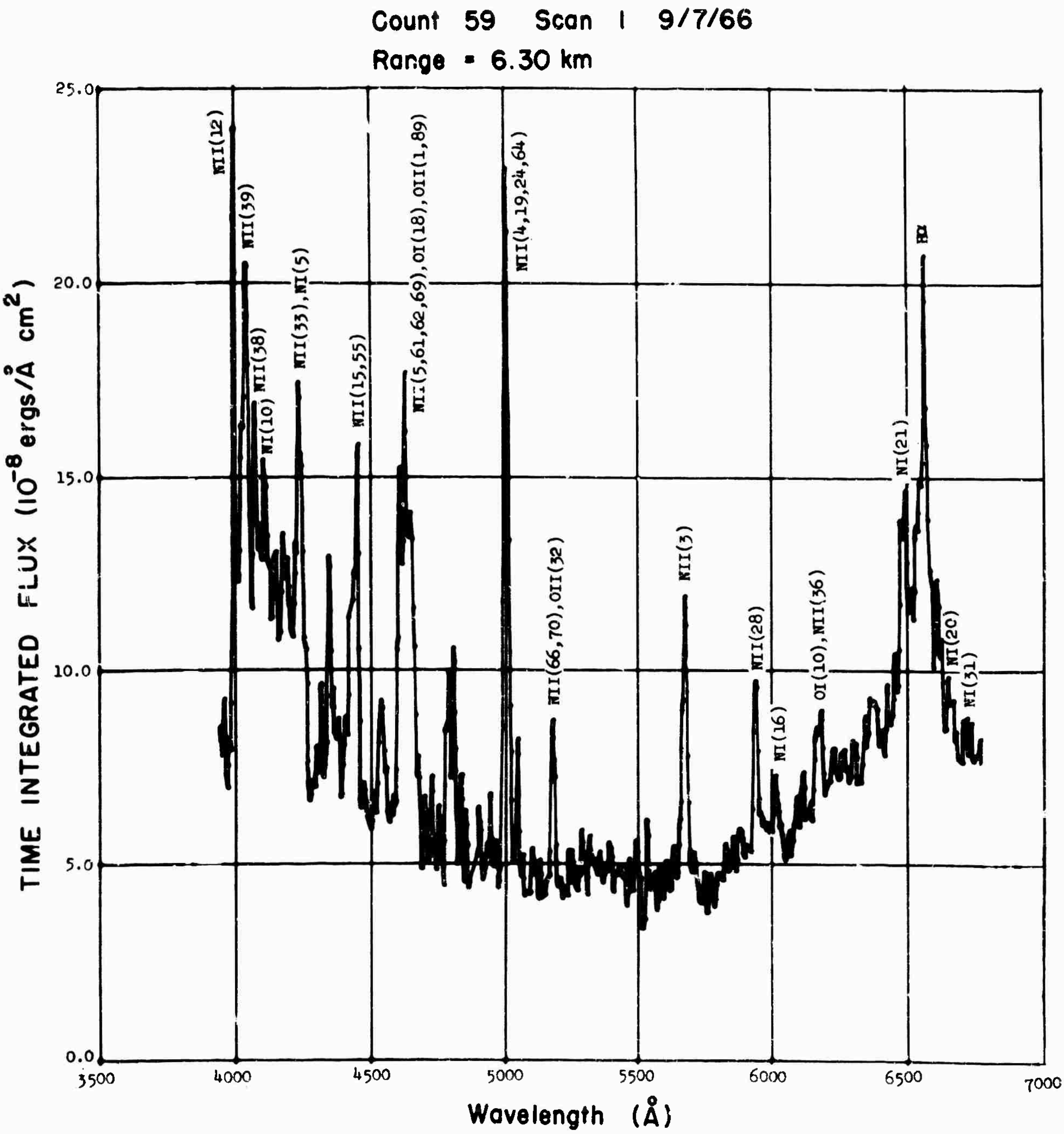

Fig. 9. Flux at spectrograph entrance pupil from ~ 20-meter length of channel, uncorrected for rain transmission. First return stroke.

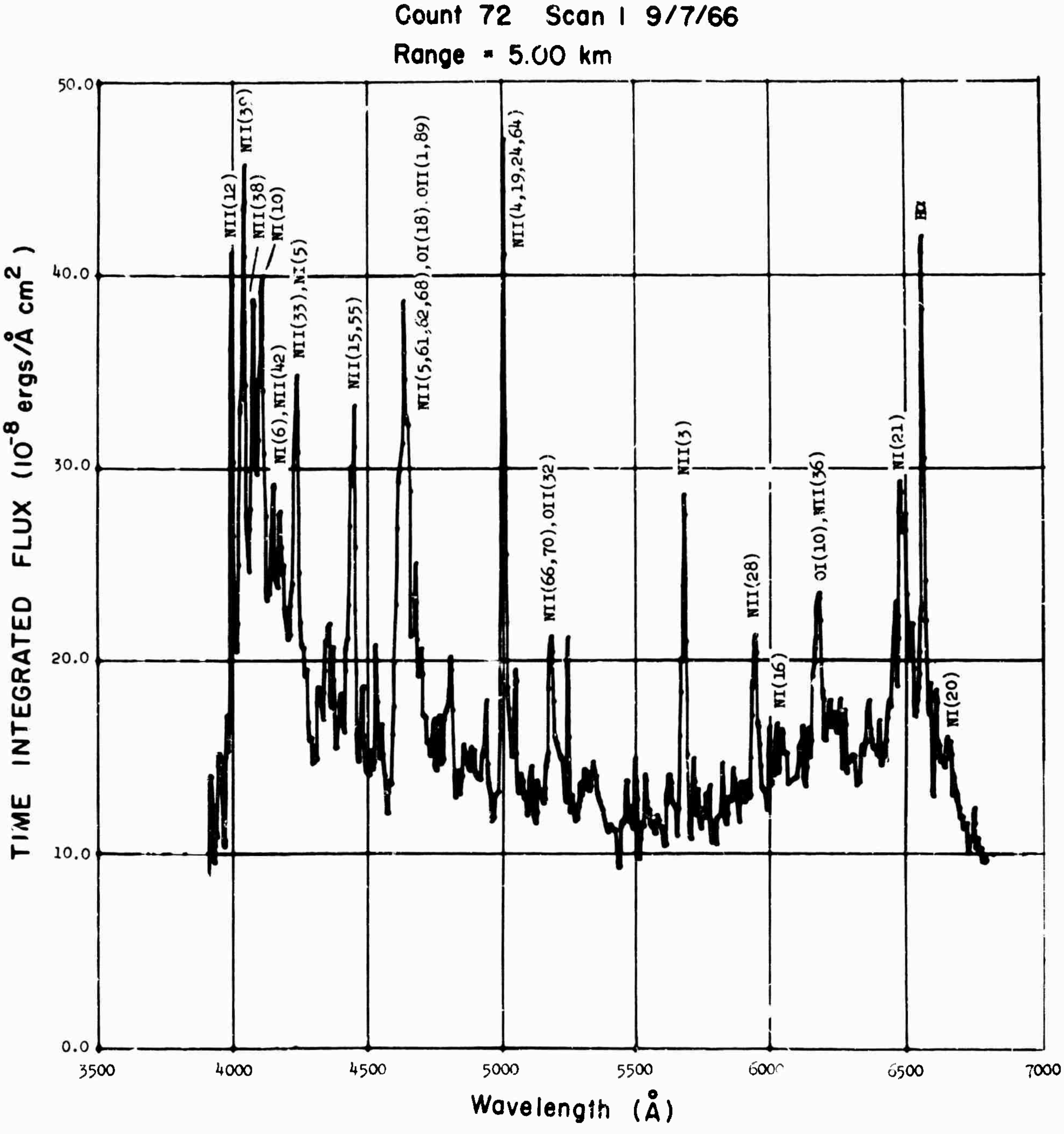

Fig. 10. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. First return stroke.

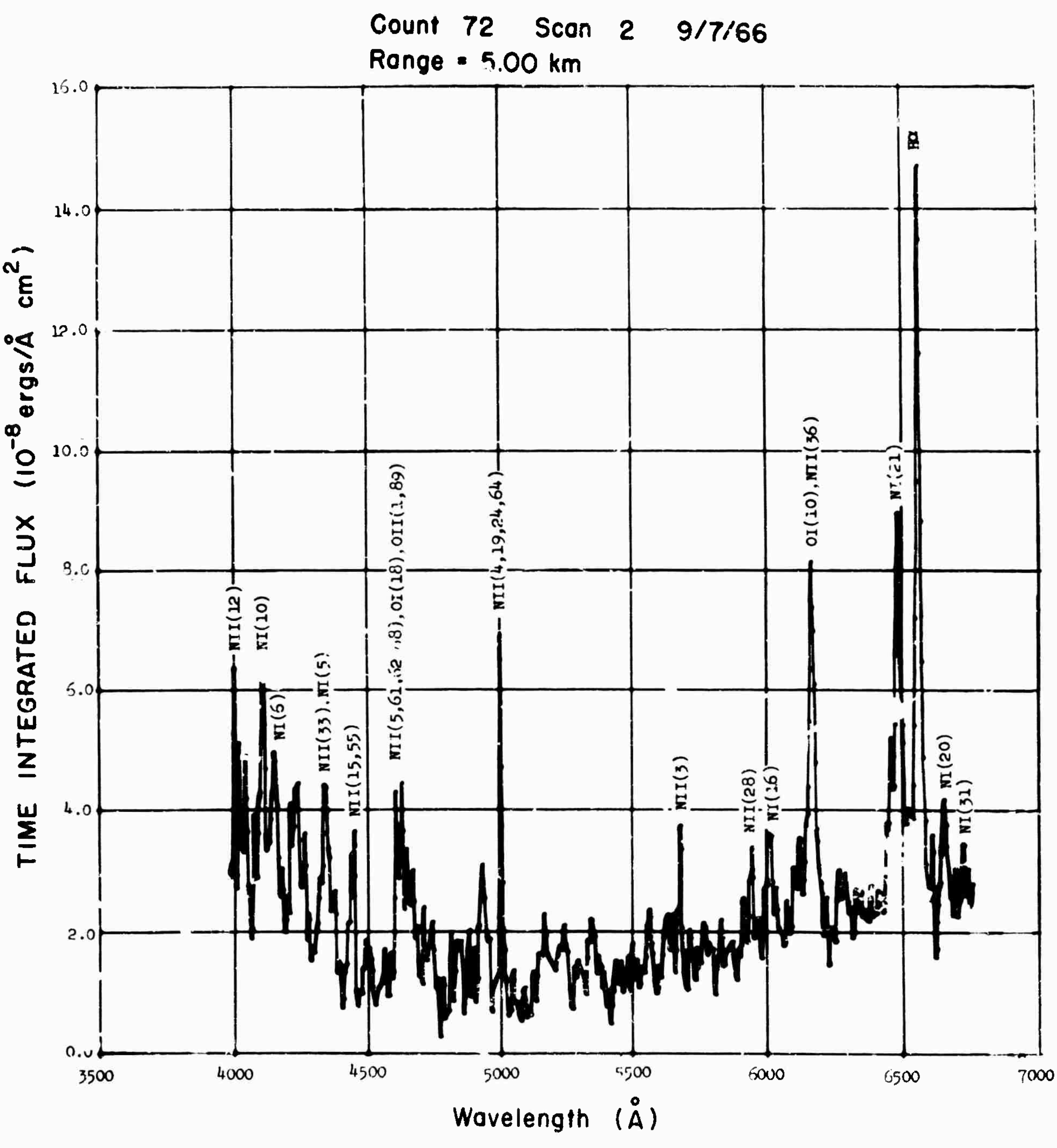

Fig. 11. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

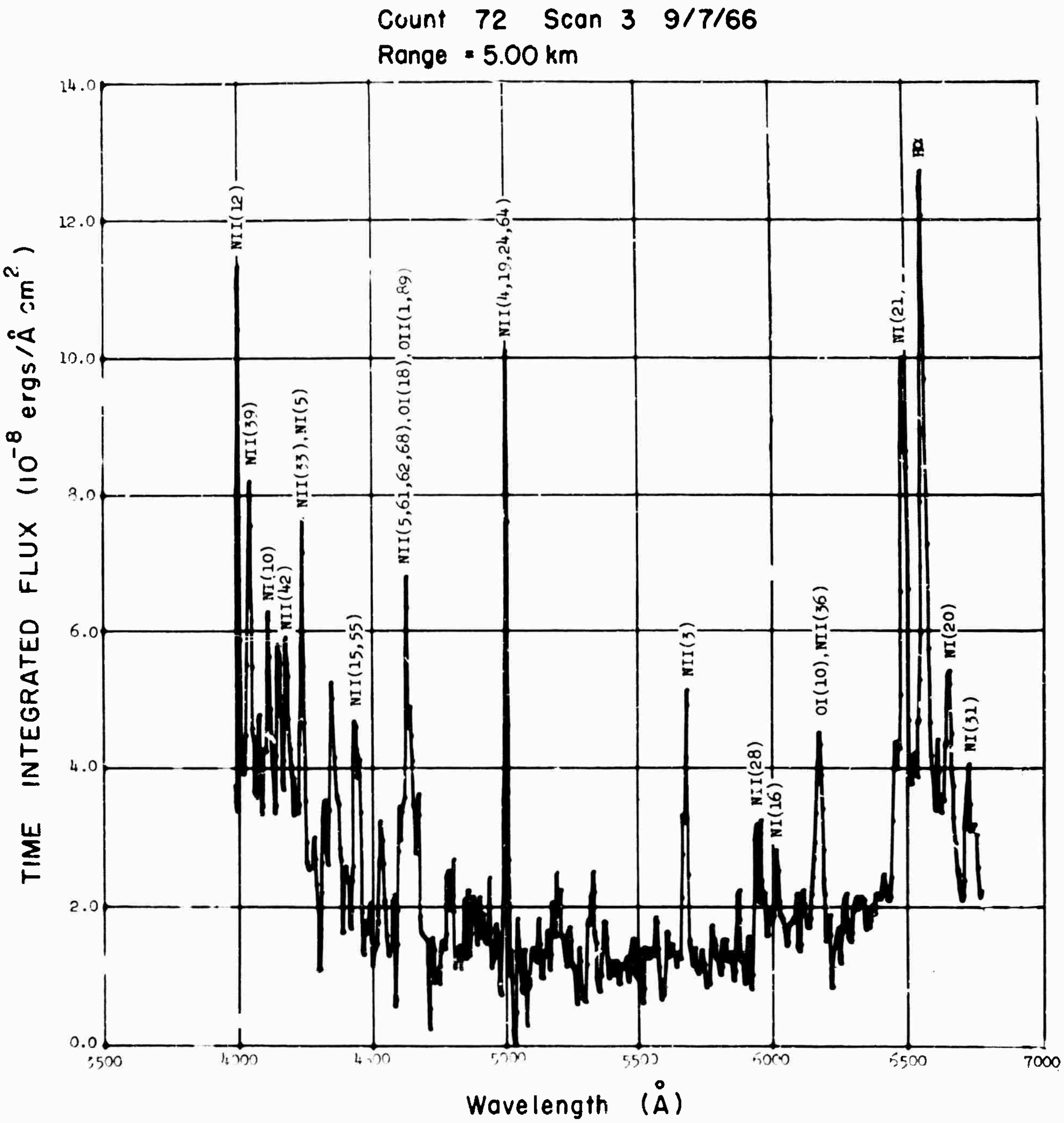

Fig. 12. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

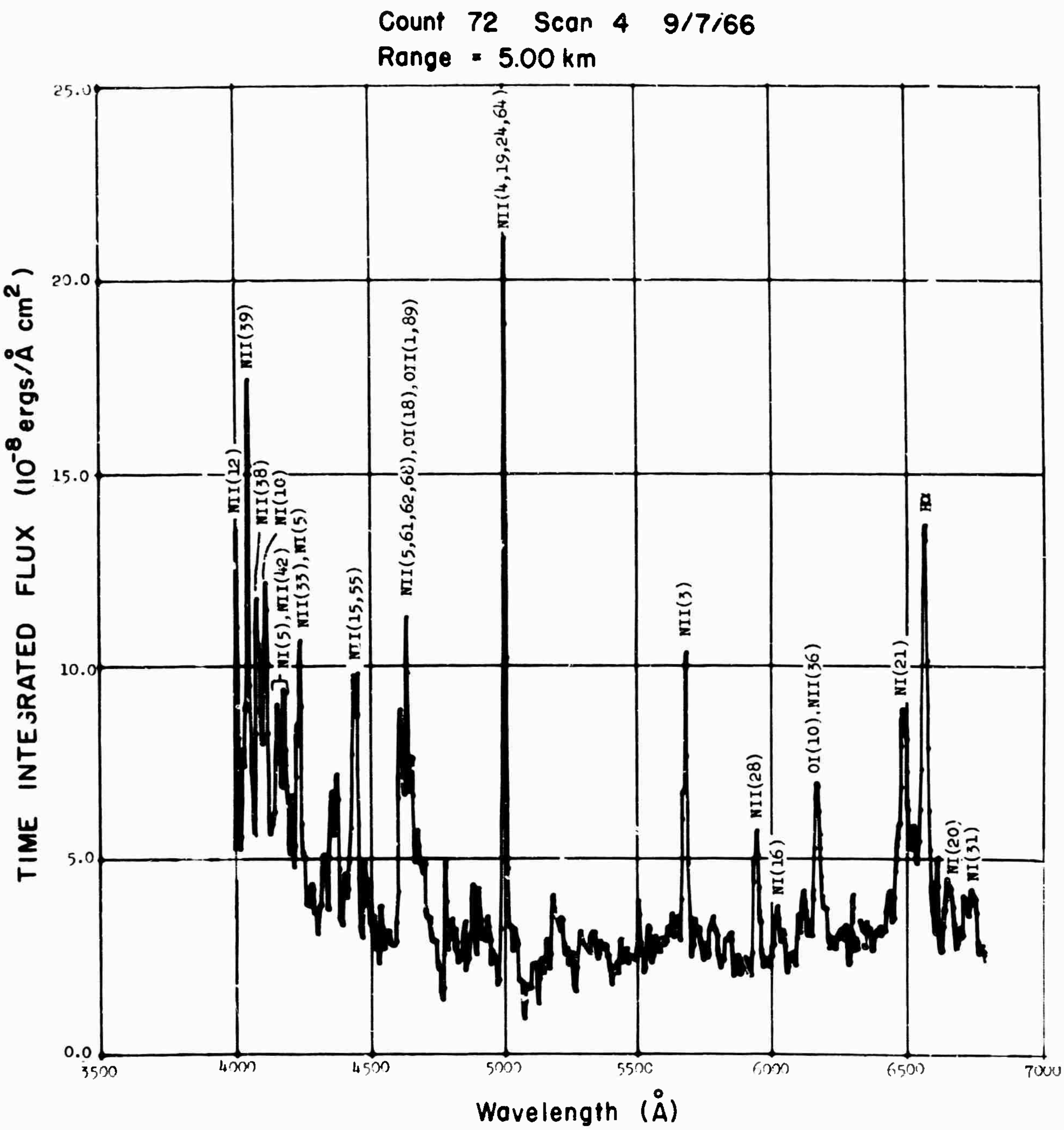

Fig. 13. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

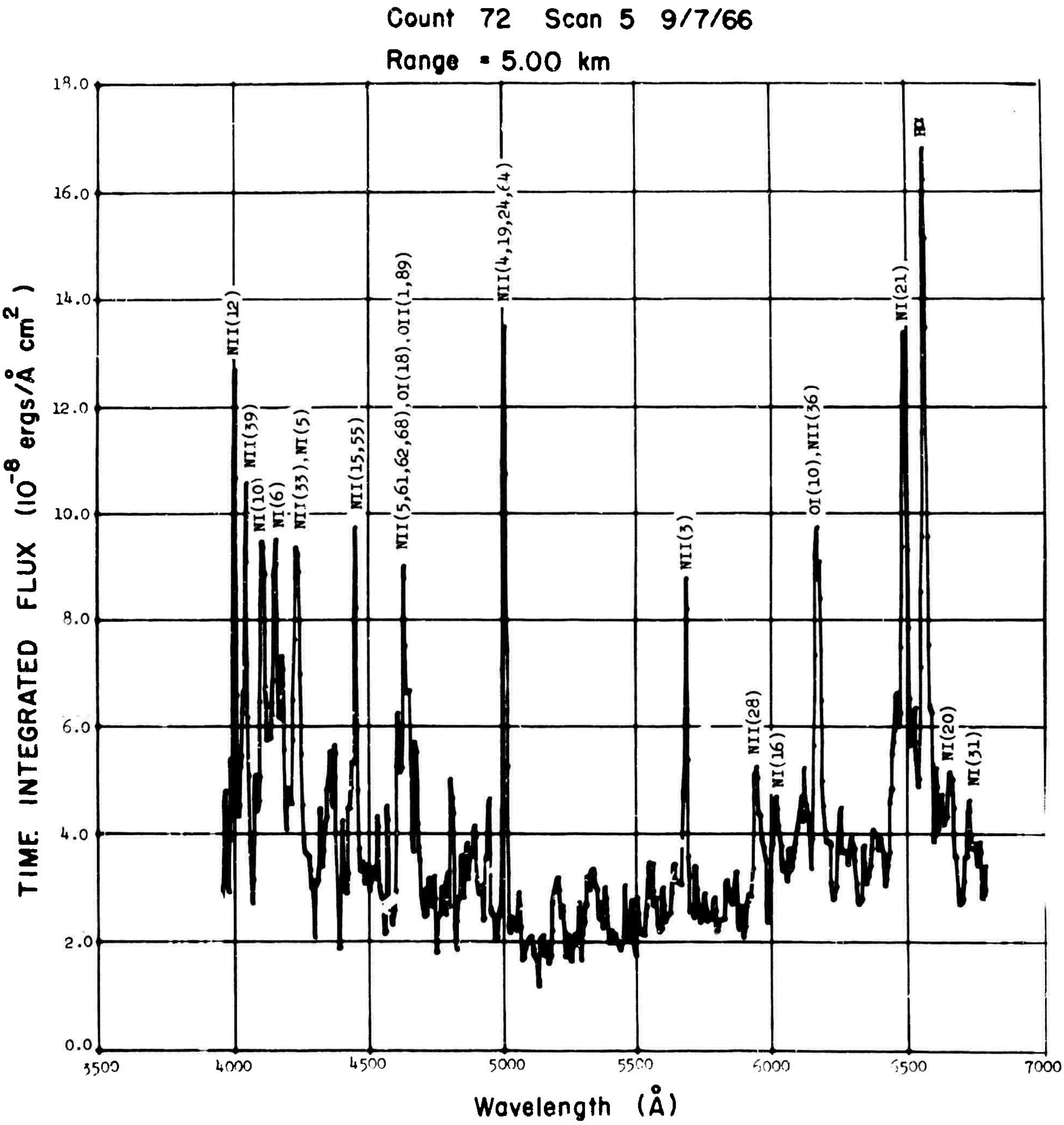

Fig. 14. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

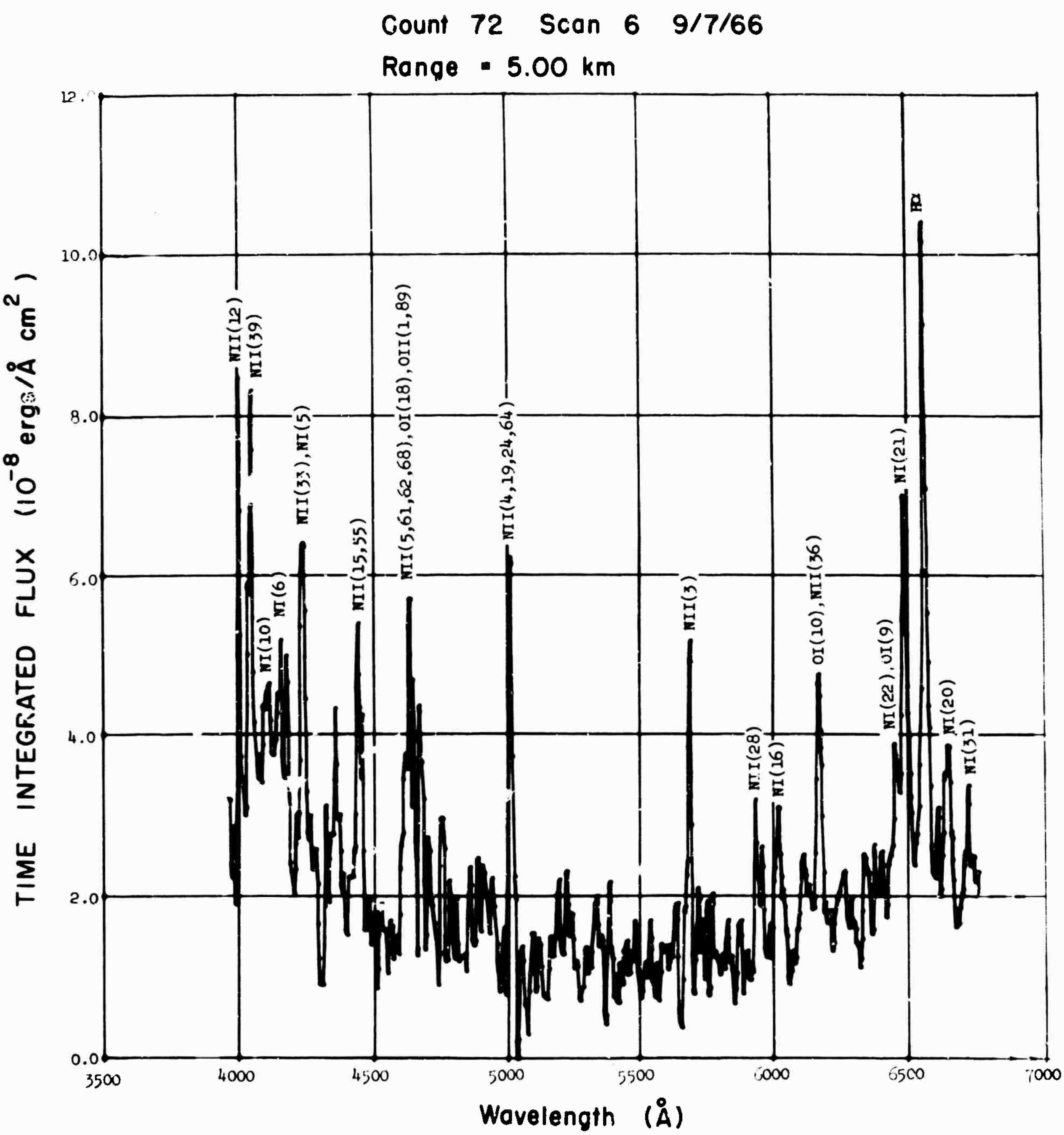

Fig. 15. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

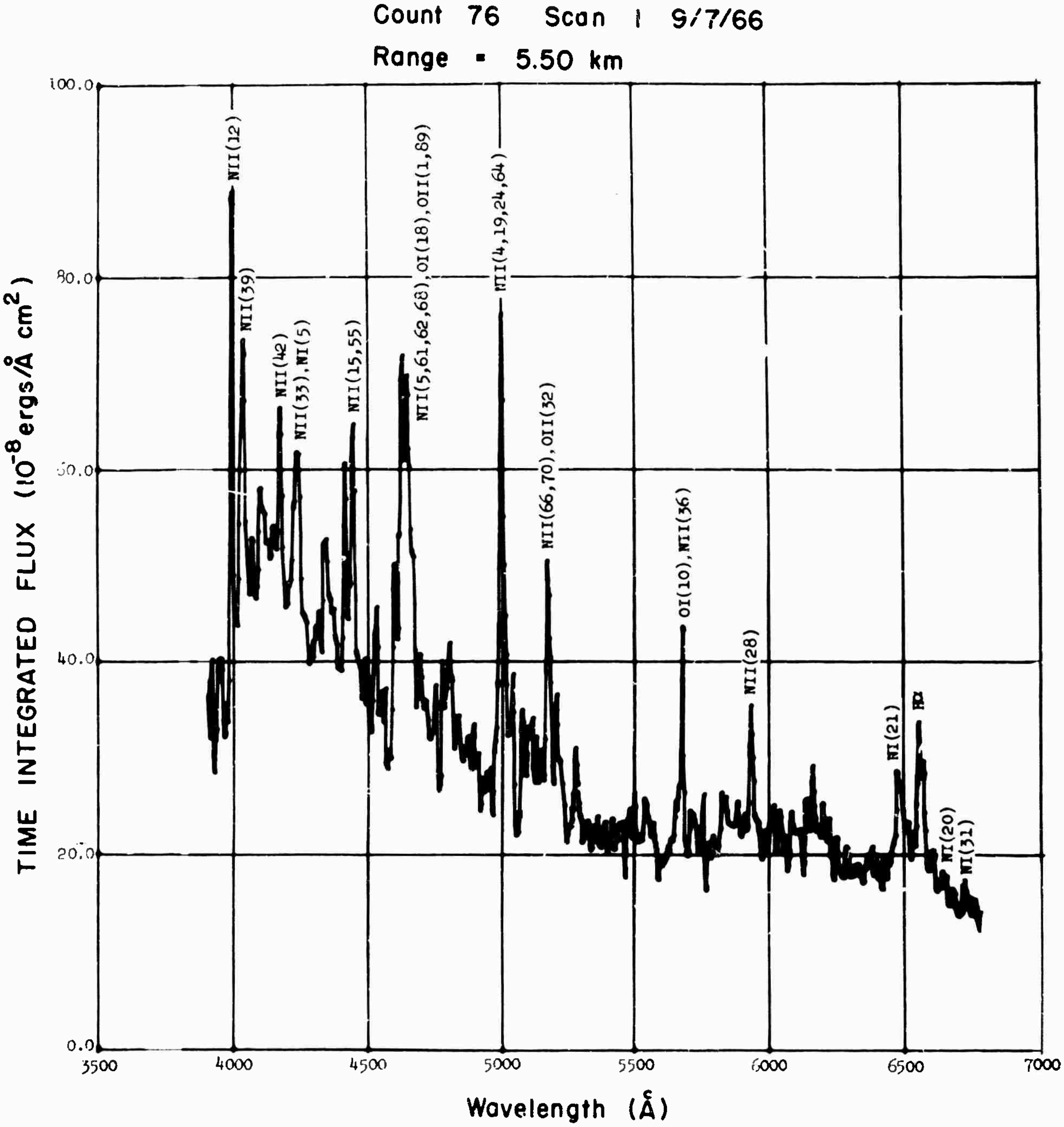

Fig. 16. Flux at spectrograph entrance pupil from ~ 17-meter length of channel, uncorrected for rain transmission. First return stroke.

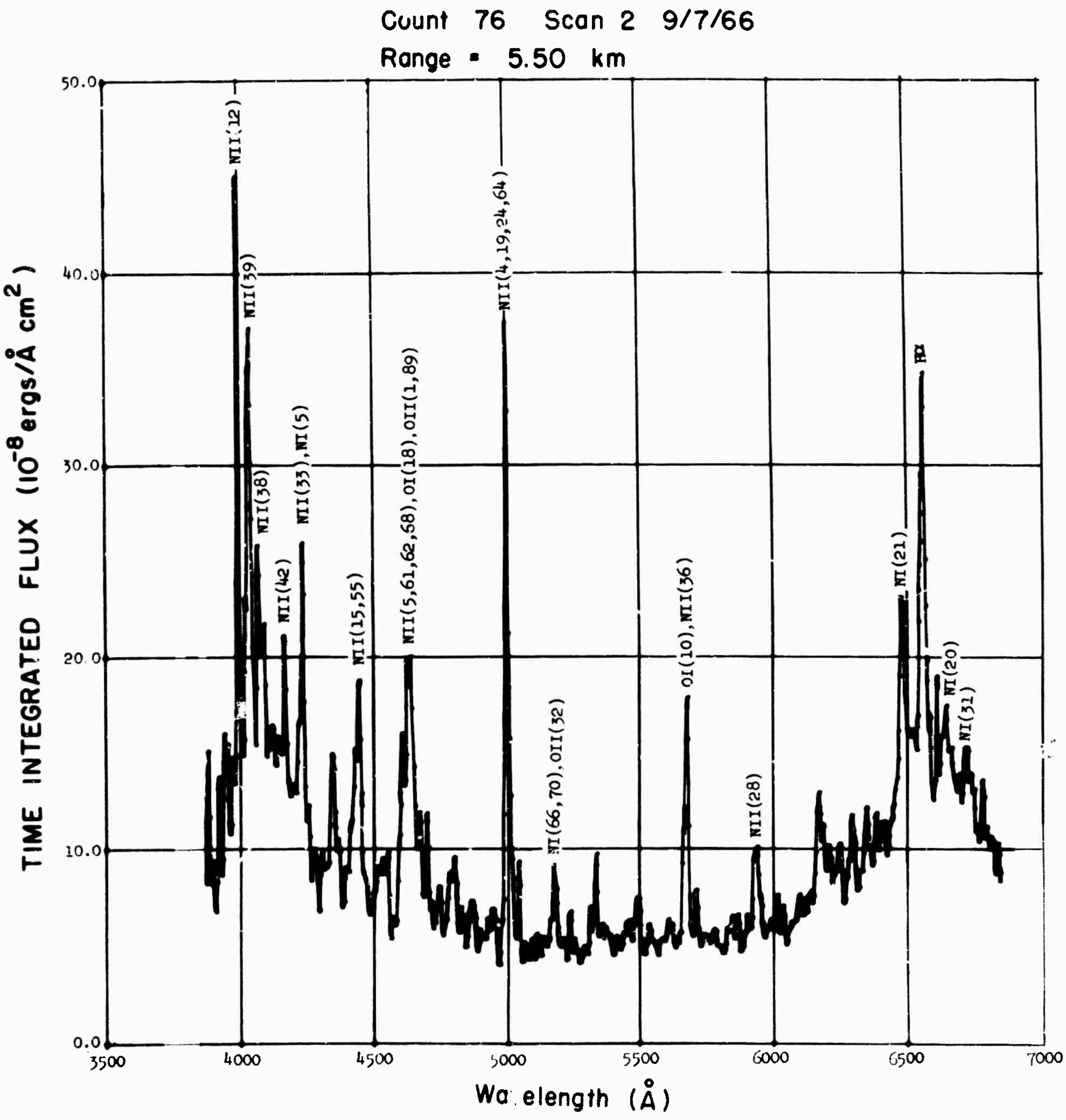

Fig. 17. Flux at spectrograph entrance pupil from ~ 17-meter length of channel, uncorrected for rain transmission. Subsequent return stroke.

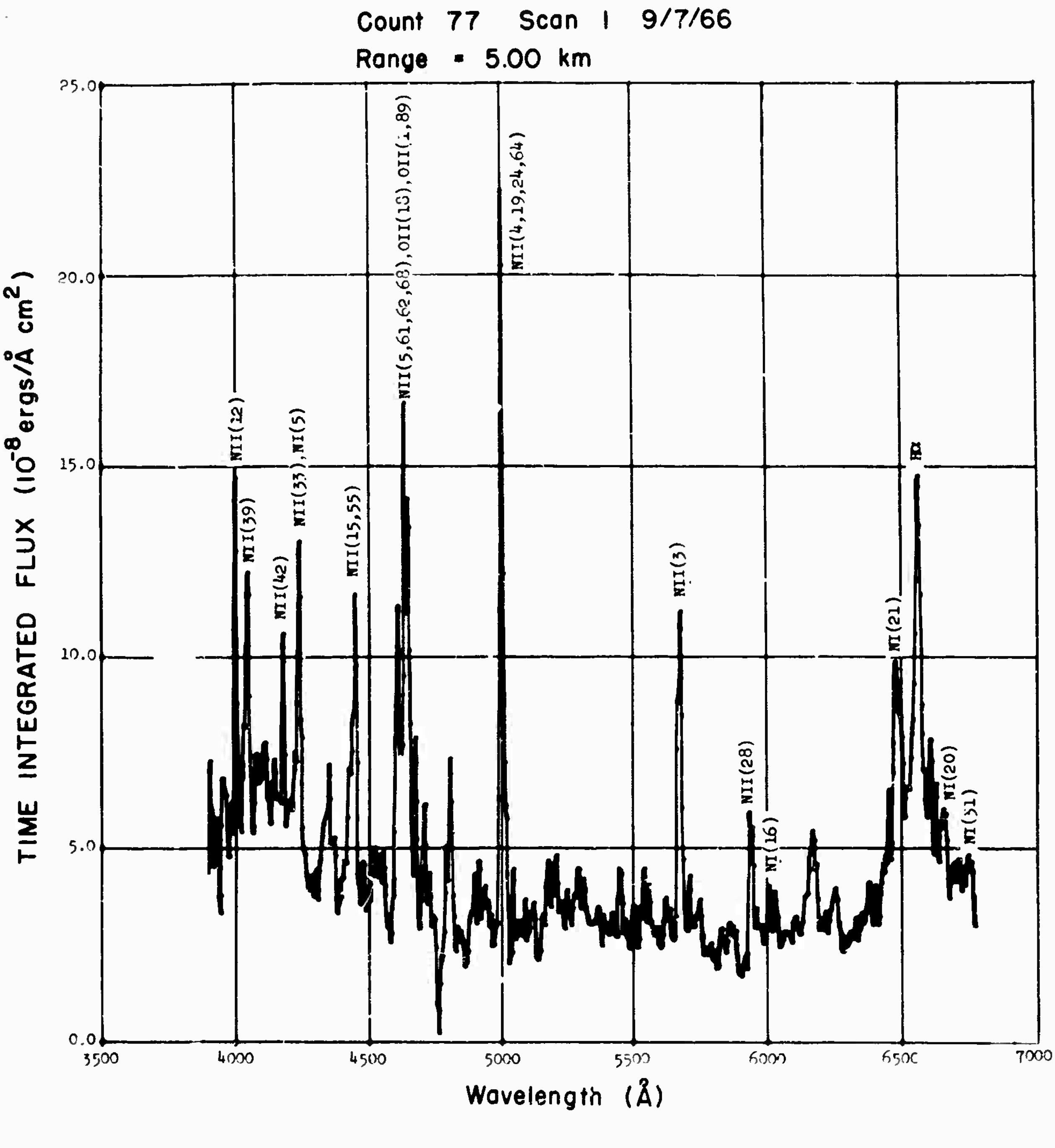

Fig. 18. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. First return stroke.

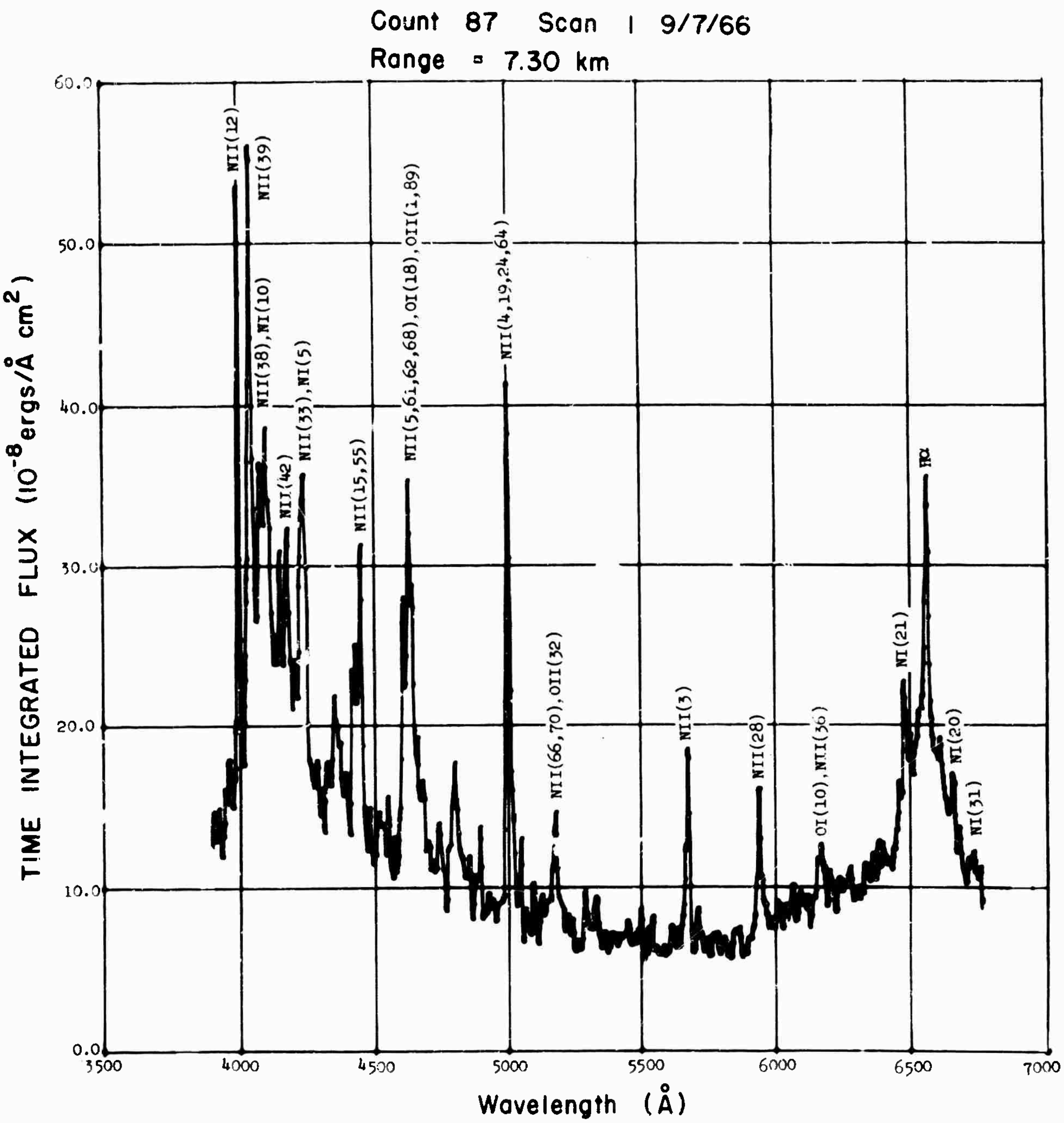

Fig. 19. Flux at spectrograph entrance pupil from ~ 23-meter length of channel, uncorrected for rain transmission. First return stroke.

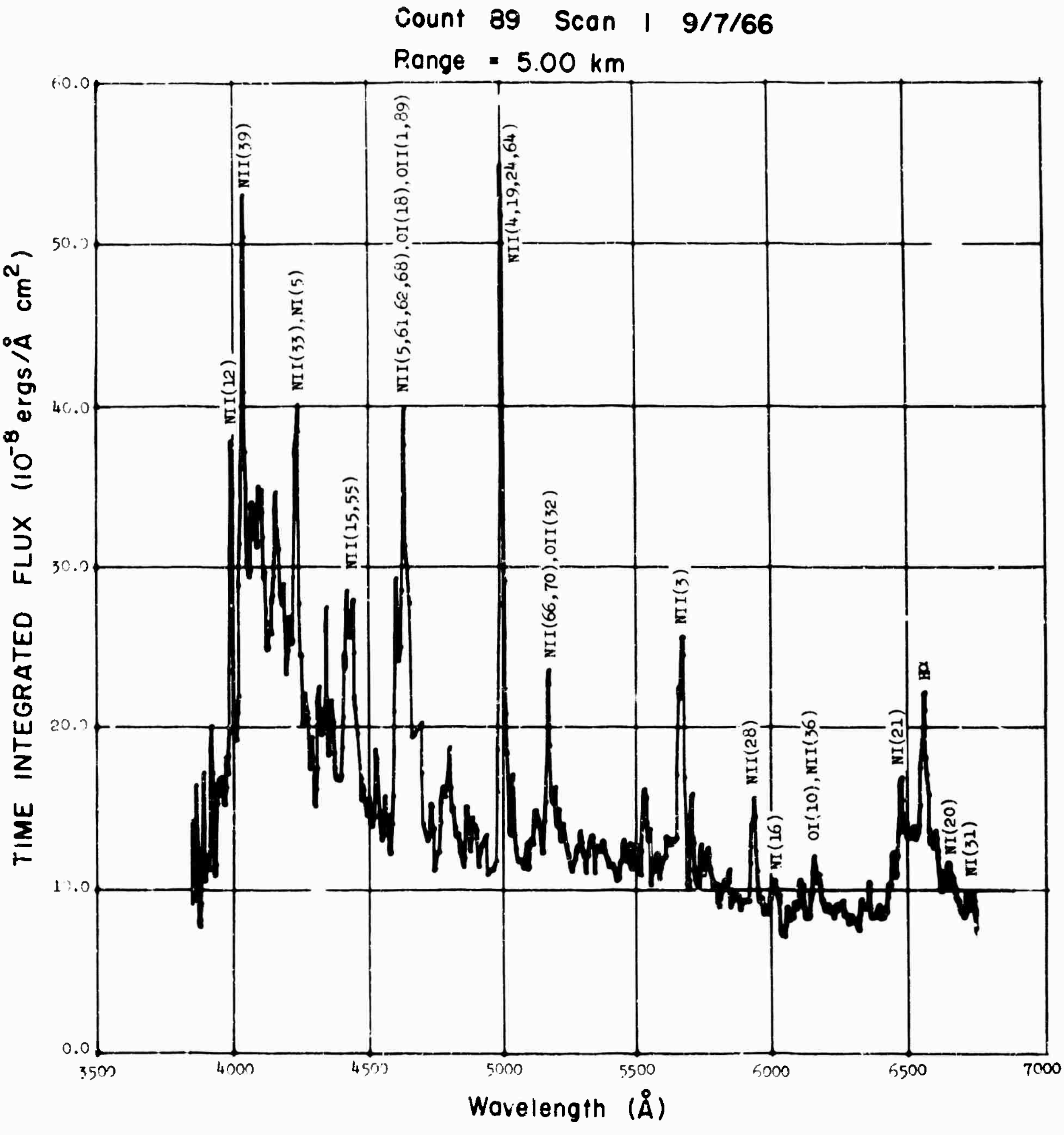

Fig. 20. Flux at spectrograph entrance pupil from ~ 16-meter length of channel, uncorrected for rain transmission. First return stroke.

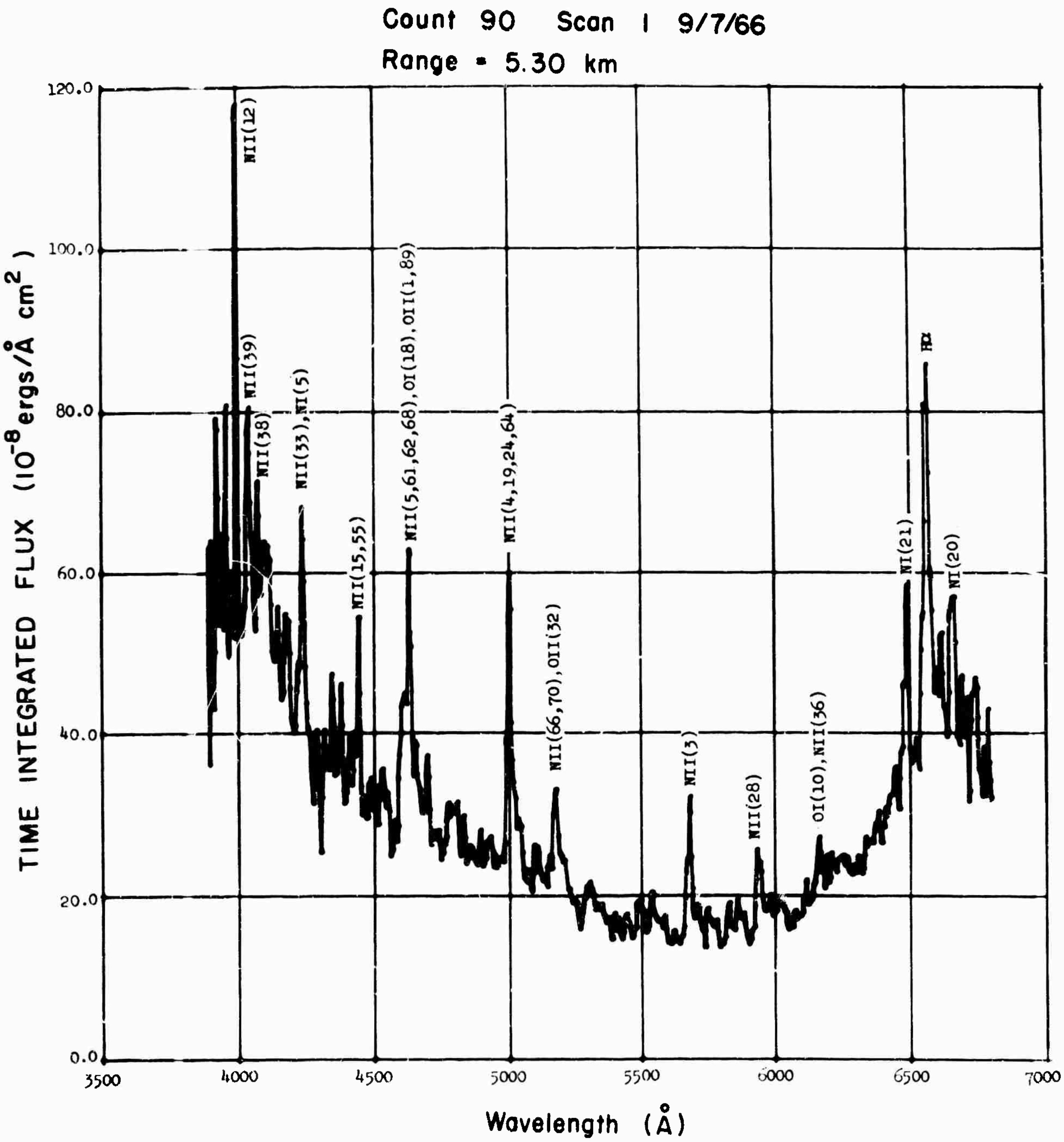

Fig. 21. Flux at spectrograph entrance pupil from ~ 17-meter length of channel, uncorrected for rain transmission. First return stroke.

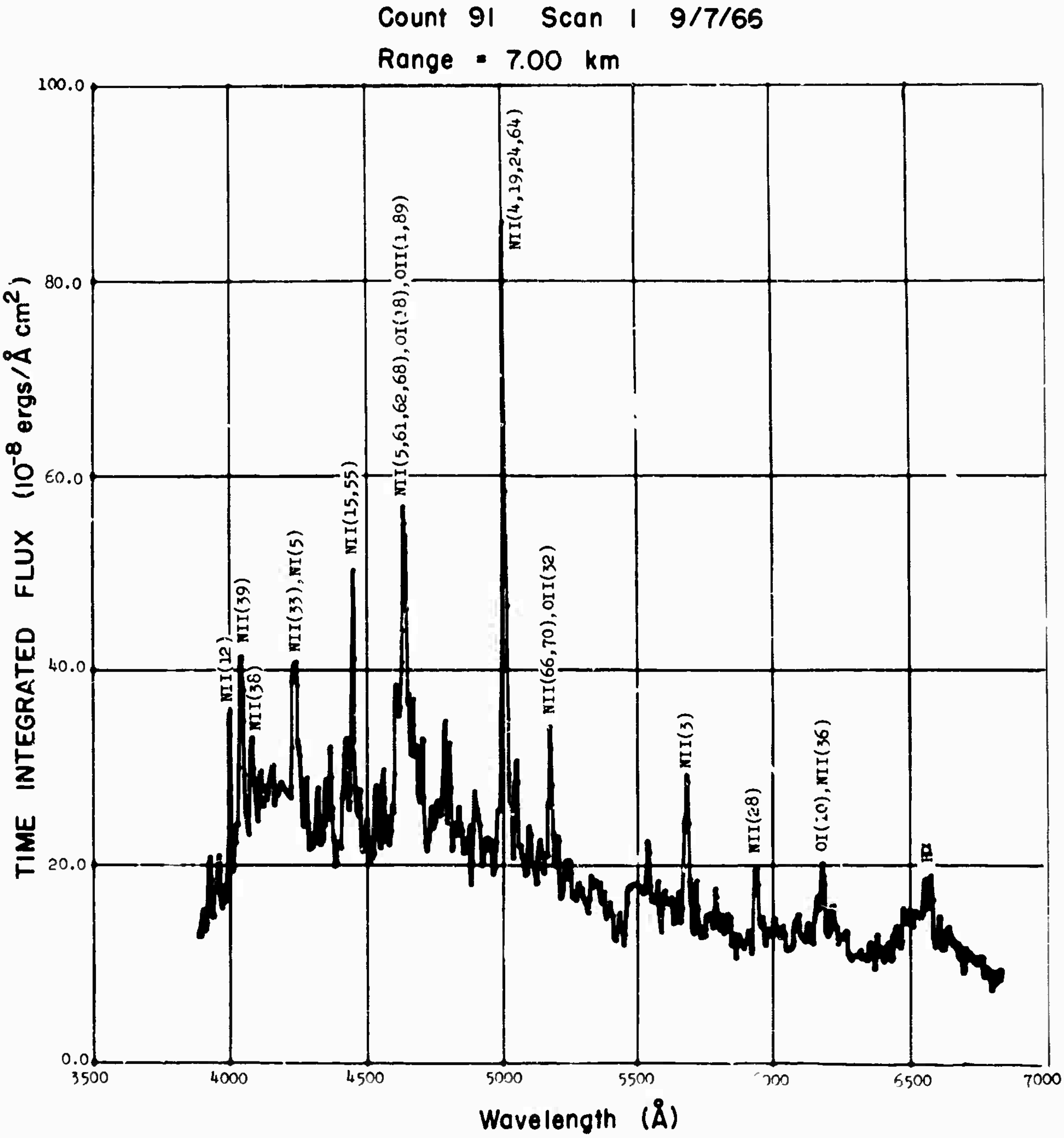

Fig. 22. Flux at spectrograph entrance pupil from ~ 22-meter length of channel, uncorrected for rain transmission. First return stroke.

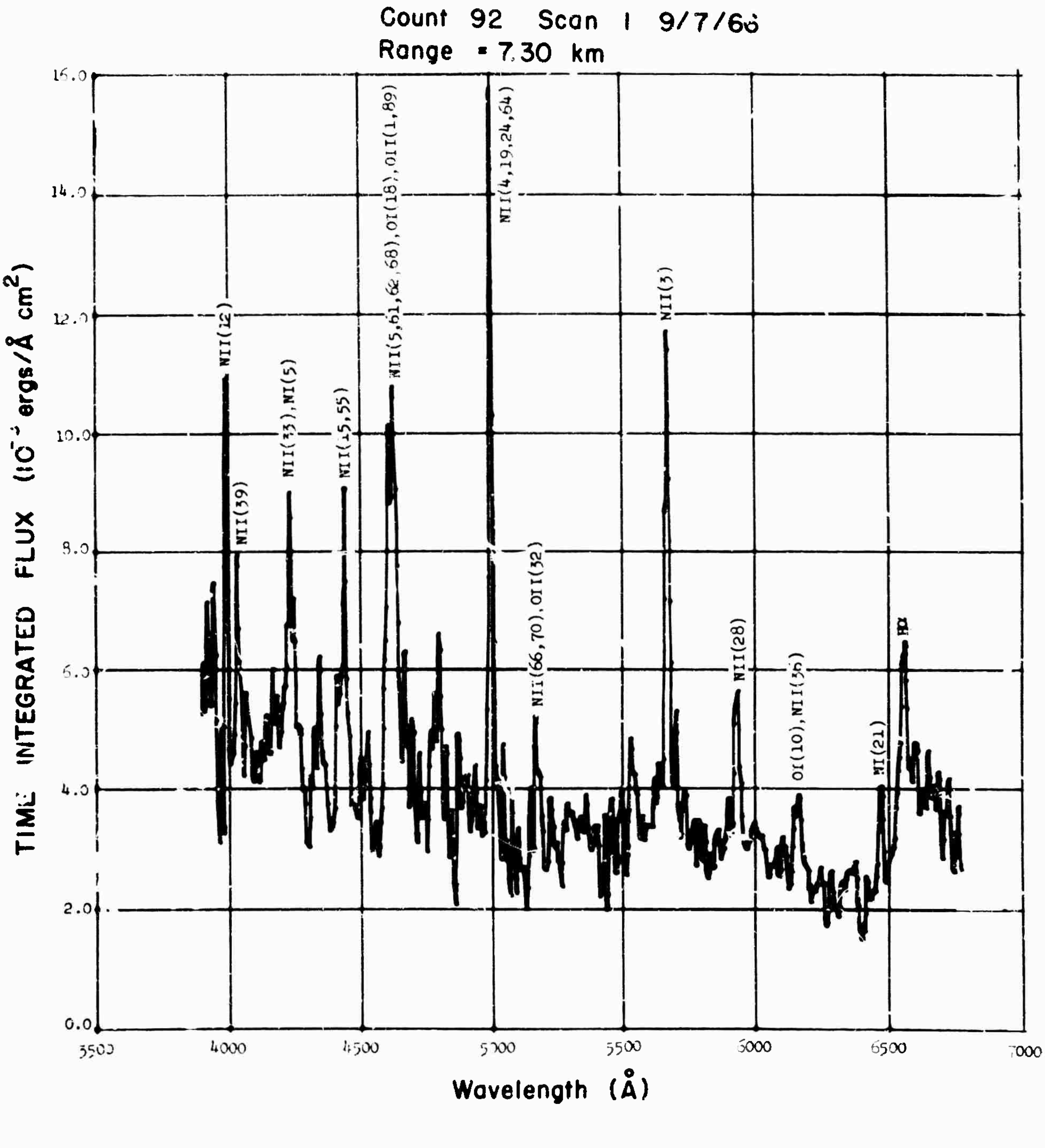

Fig. 23. Flux at spectrograph entrance pupil from ~23-meter length of channel, uncorrected for rain transmission. First return stroke.

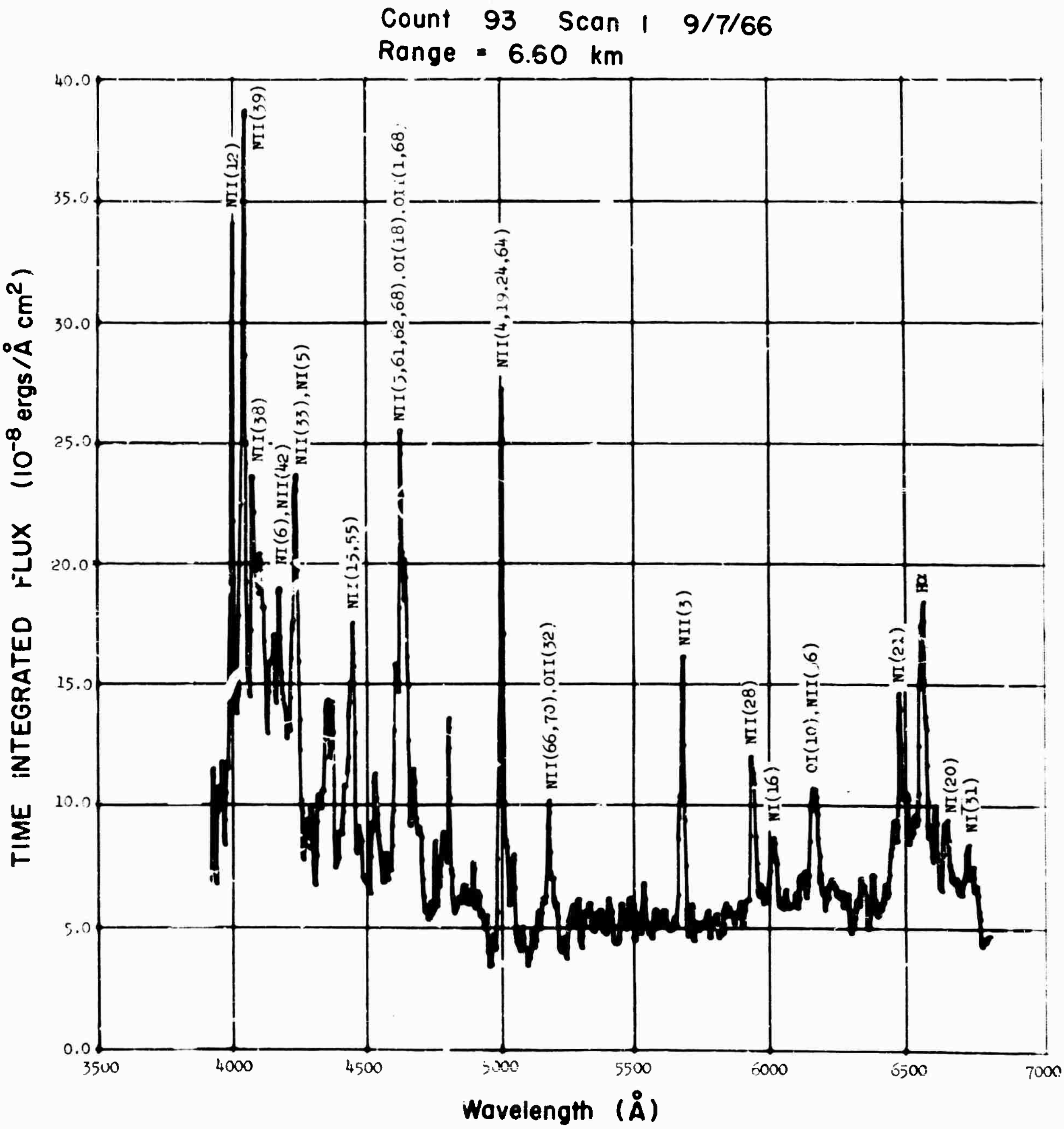

Fig. 24. Flux at spectrograph entrance pupil from ~ 21-meter length of channel, uncorrected for rain transmission. First return stroke.

Fig. 25. Count 393, Storm 30 of the 1965 lightning study.